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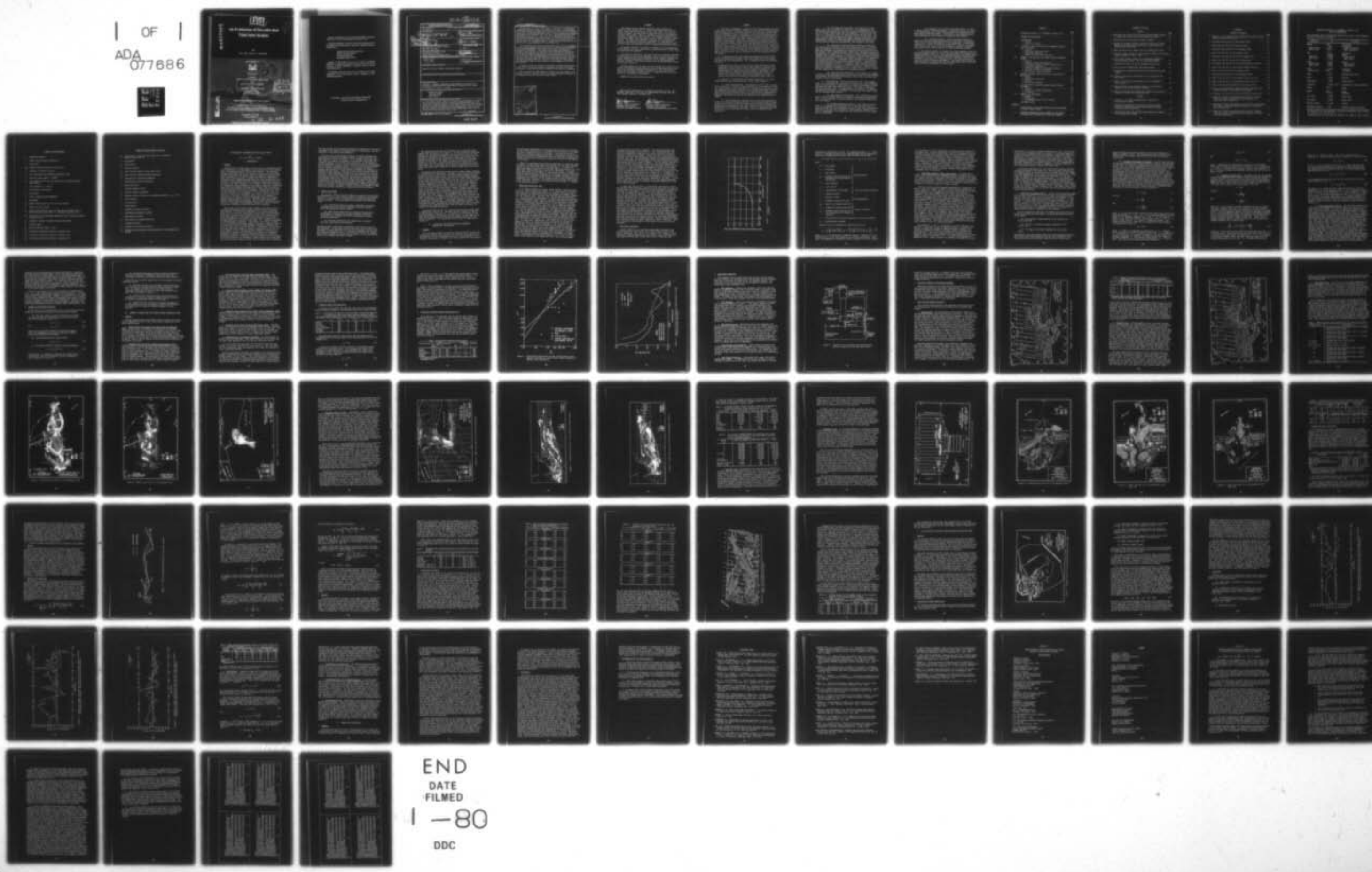

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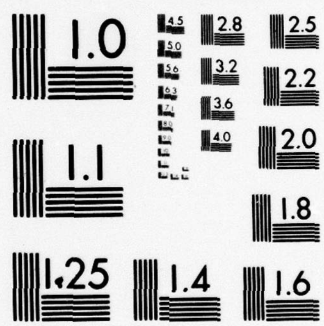
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An Evaluation of Movable-Bed Tidal Inlet Models

by

S.C. Jain and J.F. Kennedy

GITI REPORT 17

February 1979

Prepared for
U.S. Army Coastal Engineering Research Center
under
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Iowa Institute of Hydraulic Research
University of Iowa
Iowa City, Iowa 52240

GENERAL INVESTIGATION OF TIDAL INLETS

A Program of Research Conducted Jointly by
U.S. Army Coastal Engineering Research Center, Fort Belvoir, Virginia
U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi

Department of the Army
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APPENDIX B: WATERWAYS EXPERIMENT STATION COMMENTS ON THE REPORT, "AN EVALUATION OF MOVABLE-BED TIDAL INLET MODELS," prepared by H.B. Simmons, W.H. McAnally, Jr., and C.L. Vincent.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Movable-bed models
Sediment transport
Tidal hydraulics
Tidal inlets

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The objective of this study was to evaluate the effectiveness of movable-bed tidal inlet hydraulic models in predicting prototype behavior, by comparing model predictions with the observations made in the prototype, and to examine the scaling requirements for such models. Model studies of this type have been conducted in the United States and Canada only by the U.S. Army Engineer Waterways Experiment Station (WES). Seven model studies were conducted by WES during the period 1939 to 1969.

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The calibrations of five of these models, as measured by bed topography changes, are evaluated by means of quantitative indicators, including correlation coefficients and root-mean-square (rms) error. The values of correlation coefficients, disregarding measurement errors in model and prototype soundings, were generally low and those of rms error high. If combined model and prototype sounding errors of 2 to 3 feet (0.61 to 0.91 meter) were allowed, the correlation coefficients were somewhat higher and the rms errors lower. Evaluation of data from the Galveston Harbor entrance model revealed that the shoaling rates and distribution along the navigation channel predicted by the model are not in good agreement with the prototype data.

It was concluded that the model reproduction of details of bed topography was less accurate than that which might have been obtained had the proposed similitude criteria ~~proposed here~~ been used, and had more complete prototype data been available for calibration. Disagreement between model and prototype is believed to have been due to: (a) scale effects introduced by nonsimilarity of the physical processes; (b) insufficient prototype data for calibration and verification; (c) oversimplification of the available prototype data for use in the model study; and (d) experimental errors. In all cases, the prototype data utilized for model calibration were decidedly inadequate, and the similitude requirements followed, especially those related to the sediment, were deficient in light of recent advances in understanding of coastal sediment transport.

A literature review was conducted to determine the present understanding of and practice concerning similitude requirements for movable-bed coastal inlet models. Similitude conditions for models of this type are recommended.

Also, an appendix has been prepared by the WES to provide comments on the University of Iowa's findings as well as to provide additional information on the background and value of particular model studies.

FOREWORD

This report results from work performed under Contract No. DACW72-76-C-0003 between the U.S. Army Coastal Engineering Research Center (CERC) and The University of Iowa, Iowa City. It is one in a series of reports from the Corps of Engineers' General Investigation of Tidal Inlets (GITI), which is under the technical surveillance of CERC and is conducted by CERC, the U.S. Army Engineer Waterways Experiment Station (WES), other government agencies, and by private organizations. The report was prepared to acquaint U.S. Army Engineer Districts and Divisions with the capabilities and limitations of movable-bed tidal inlet hydraulic models in predicting prototype behavior.

An appendix (by WES) is included to comment on the interpretation of the report, and on the application to movable-bed inlet studies made for Corps District purposes.

The study was conducted at the Iowa Institute of Hydraulic Research, The University of Iowa, by Dr. Subhash C. Jain, Associate Professor of Energy Engineering and Research Engineer, and Dr. John F. Kennedy, Professor of Energy Engineering and Director of the Iowa Institute of Hydraulic Research. They were assisted by Ms. Nai-Drwang Hsueh, Graduate Research Assistant.

The Iowa authors wish to thank the staff at WES and at CERC for providing the background information and data, offering many helpful comments, and critically reviewing the manuscript. The assistance of several of the Engineer District Offices in supplying model and field data also is gratefully acknowledged.

Comments on the publication are invited.

Approved for publication in accordance with Public Law 116, 79th Congress, approved 31 July 1945, as supplemented by Public Law 172, 88th Congress, approved 7 November 1963.

John L. Cannon	John H. Cousins
JOHN L. CANNON	JOHN H. COUSINS
Colonel, Corps of Engineers	Colonel, Corps of Engineers
Commander and Director	Commander and Director
Waterways Experiment Station	Coastal Engineering Research Center

PREFACE

1. The Corps of Engineers, through its Civil Works program, has sponsored, over the past 23 years, research into the behavior and characteristics of tidal inlets. The Corps' interest in tidal inlet research stems from its responsibilities for navigation, beach erosion prevention and control, and flood control. Tasked with the creation and maintenance of navigable U.S. waterways, the Corps dredges millions of cubic yards of material each year from tidal inlets that connect the ocean with bays, estuaries, and lagoons. Design and construction of navigation improvements to existing tidal inlets are an important part of the work of many Corps' offices. In some cases, design and construction of new inlets are required. Development of information concerning the hydraulic characteristics of inlets is important not only for navigation and inlet stability, but also because inlets, by allowing for the ingress of storm surges and egress of flood waters, play an important role in the flushing of bays and lagoons.

2. A research program, the General Investigation of Tidal Inlets (GITI), was developed to provide quantitative data for use in design of inlets and inlet improvements. It is designed to meet the following objectives:

> *To determine* the effects of wave action, tidal flow, and related phenomena on inlet stability and on the hydraulic, geometric, and sedimentary characteristics of tidal inlets; to develop the knowledge necessary to design effective navigation improvements, new inlets, and sand transfer systems at existing tidal inlets; to evaluate the water transfer and flushing capability of tidal inlets; and to define the processes controlling inlet stability.

3. The GITI is divided into three major study areas: (a) inlet classification, (b) inlet hydraulics, and (c) inlet dynamics.

a. Inlet Classification. The objectives of the inlet classification study are to classify inlets according to their geometry, hydraulics, and stability, and to determine the relationships that exist among the geometric and dynamic characteristics and the environmental factors that control these characteristics. The classification study keeps the general investigation closely related to real inlets and produces an important inlet data base useful in documenting the characteristics of inlets.

b. Inlet Hydraulics. The objectives of the inlet hydraulics study are to define tide-generated flow regime and water level fluctuations in the vicinity of coastal inlets and to develop techniques for predicting these phenomena. The inlet hydraulics study is divided into three areas: (1) idealized inlet model study, (2) evaluation of state-of-the-art physical and numerical models, and (3) prototype inlet hydraulics.

(1) The Idealized Inlet Model. The objectives of this model study are to determine the effect of inlet configurations and structures on discharge, head loss and velocity distribution for a number of realistic inlet shapes and tide conditions. An initial set of tests in a trapezoidal inlet was conducted between 1967 and 1970. However, in order that subsequent inlet models are more representative of real inlets, a number of "idealized" models representing various inlet morphological classes are being developed and tested. The effects of jetties and wave action on the hydraulics are included in the study.

(2) Evaluation of State-of-the-Art Modeling Techniques. The objectives of this part of the inlet hydraulics study are to determine the usefulness and reliability of existing physical and numerical modeling techniques in predicting the hydraulic characteristics of inlet-bay systems, and to determine whether simple tests, performed rapidly and economically, are useful in the evaluation of proposed inlet improvements. Masonboro Inlet, North Carolina, was selected as the prototype inlet which would be used along with hydraulic and numerical models in the evaluation of existing techniques. In September 1969 a complete set of hydraulic and bathymetric data was collected at Masonboro Inlet. Construction of the fixed-bed physical model was initiated in 1969, and extensive tests have been performed since then. In addition, three existing numerical models were applied to predict the inlet's hydraulics. Extensive field data were collected at Masonboro Inlet in August 1974 for use in evaluating the capabilities of the physical and numerical models.

(3) Prototype Inlet Hydraulics. Field studies at a number of inlets are providing information on prototype inlet-bay tidal hydraulic relationships and the effects of friction, waves, tides, and inlet morphology on these relationships.

c. *Inlet Dynamics*. The basic objective of the inlet dynamics study is to investigate the interactions of tidal flow, inlet configuration, and wave action at tidal inlets as a guide to improvement of inlet channels and nearby shore protection works. The study is subdivided into four specific areas: (1) model materials evaluation, (2) movable-bed modeling evaluation, (3) reanalysis of a previous inlet model study, and (4) prototype inlet studies.

(1) Model Materials Evaluation. This evaluation was initiated in 1969 to provide data on the response of movable-bed model materials to waves and flow to allow selection of the optimum bed materials for inlet models.

(2) Movable-Bed Model Evaluation. The objective of this study is to evaluate the state-of-the-art of modeling techniques, in this case movable-bed inlet modeling. Since, in many cases, movable-bed modeling is the only tool available for predicting the response of an inlet to improvements, the capabilities and limitations of these models must be established.

(3) Reanalysis of an Earlier Inlet Model Study. In 1975, a report entitled, "Preliminary Report: Laboratory Study of the Effect of an Uncontrolled Inlet on the Adjacent Beach," was published by the Beach Erosion Board (now CERC). A reanalysis of the original data is being performed to aid in planning of additional GITI efforts.

(4) Prototype Dynamics. Field and office studies of a number of inlets are providing information on the effects of physical forces and artificial improvements on inlet morphology. Of particular importance are studies to define the mechanisms of natural sand bypassing at inlets, the response of inlet navigation channels to dredging and natural forces, and the effects of inlets on adjacent beaches.

4. This report presents the results of a study conducted as part of the inlet dynamics effort to satisfy the requirements of paragraph 3c(2), Movable-Bed Model Evaluation. Five movable-bed tidal inlet model studies conducted at the U.S. Army Engineer Waterways Experiment Station were evaluated for accuracy of a calibration and a sixth was evaluated for ability to predict prototype performance. This report also reviews the state-of-the-art of movable-bed tidal inlet modeling practice and recommends similitude requirements for these models.

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FIGURES--Continued

CONVERSION FACTORS, U.S. CUSTOMARY TO METRIC (SI) UNITS OF MEASUREMENT

U.S. customary units of measurement used in this report can be converted to metric (SI) units as follows:

Multiply	by	To obtain
inches	25.4	millimeters
	2.54	centimeters
square inches	6.452	square centimeters
cubic inches	16.39	cubic centimeters
feet	30.48	centimeters
	0.3048	meters
square feet	0.0929	square meters
cubic feet	0.0283	cubic meters
yards	0.9144	meters
square yards	0.836	square meters
cubic yards	0.7646	cubic meters
miles	1.6093	kilometers
square miles	259.0	hectares
knots	1.852	kilometers per hour
acres	0.4047	hectares
foot-pounds	1.3558	newton meters
millibars	1.0197×10^{-3}	kilograms per square centimeter
ounces	28.35	grams
pounds	453.6	grams
	0.4536	kilograms
ton, long	1.0160	metric tons
ton, short	0.9072	metric tons
degrees (angle)	0.01745	radians
Fahrenheit degrees	5/9	Celsius degrees or Kelvins[1]

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use formula: C = (5/9) (F -32).

To obtain Kelvin (K) readings, use formula: K = (5/9) (F -32) + 273.15.

SYMBOLS AND DEFINITIONS

A	dependent variable
C	Chezy's bed-resistance coefficient
D	water depth
D_{ij}	change in bottom elevation at point (i,j)
d	diameter of sediment particles
E	root-mean-square error defined by equation (25)
F_*	particle Froude number = $V_*/\sqrt{g\gamma'd}$
F_j	total amount of fill per unit width over jth profile during a given time Δt
G	grain parameter = $(\gamma' g d^3)/\nu^2$
g	gravitational acceleration
H	wave height
k	error in measuring bed topography
L	wavelength
M_j	number of data points in the jth cross section
N	number of cross sections
Q_j	sum of total amount of scour and fill per unit width over jth profile during a given time Δt, defined by equation (23)
Q'_j	measure of the average depth change over the jth profile, defined by equation (21)
q_s	volumetric sediment transport rate per unit width
R	Reynolds number
R_*	Particle Reynolds number = V_*d/ν
R_D	correlation coefficient defined by equation (20)
R_Q	correlation coefficient defined by equation (24)
R'_Q	correlation coefficient defined by equation (22)

SYMBOLS AND DEFINITIONS--Continued

S_j total amount of scour per unit width over jth profile during a given time Δt

T wave period

T_t tidal period

V current velocity

V_* shear velocity based on total shear stress

V_{*c} shear velocity based on current shear only

X characteristic horizontal dimension

Y characteristic vertical dimension

α model distortion

γ specific weight of fluid

γ_s specific weight of sediment

γ' apparent specific weight of the submerged sediment = $(\gamma_s - \gamma'/\gamma)$

θ wave direction

λ scaling factor

μ ripple factor

ν kinematic viscosity of water

π dimensionless dependent variable

ρ mass density of water

ρ_s mass density of sediment particles

σ standard deviation

σ_g sediment-size standard deviation

σ_w parameter which describes the distribution of wave heights and periods

AN EVALUATION OF MOVABLE-BED TIDAL INLET MODELS

by

S.C. Jain and J.F. Kennedy

I. INTRODUCTION

1. General.

Stabilization of tidal inlets is one of the major engineering problems encountered in the development of many harbors and in the maintenance of navigation channels to bays and estuaries. The planning, design, and modification of tidal inlets to ensure that they perform satisfactorily under the dynamic conditions generally characterizing their surroundings is at best a complex and uncertain undertaking. Prediction of the sedimentary response of an inlet to artificial improvements and to changing ambient conditions, and optimization of the layout of training works installed to minimize undesirable accretion or erosion, are major elements in the design of tidal inlet structures. The sedimentary response depends on the complex interaction between the fluid motion and sediment transport which results from the combined effects of short-period waves (wind waves), long-period waves (tides), and unidirectional flows (river discharges). The present lack of a reliable formulation of the dynamics of sediment motion and the complexity of tidal inlet hydrography, wave action, and tidal flow patterns make it difficult to predict analytically the transport of sediment and the changes in the bed topography which will accompany specific modifications to an inlet. For this reason movable-bed hydraulic models have been employed, despite their questionable reliability, to investigate the sedimentary response of inlets to modifications and to guide the design of tidal inlet structures.

The success of any physical model depends on the proper choice of similitude requirements and the extent to which they are satisfied. Unfortunately, the similitude requirements for coastal movable-bed models are still not well established, because many of the phenomena constituent to the processes involved are yet to be adequately elucidated and formulated. The required size and density of the model mobile-bed material, the required wave and current exaggeration, the maximum permissible distortion in the model, etc., cannot be determined by straightforward calculation. Regrettably, the accuracy of model results in predicting prototype behavior continues to depend largely on the experience and skill of the engineer who designs the model, conducts the study, and interprets the data. Consequently, the execution of movable-bed model studies of regions influenced by tidal flow is still largely an "art" and entails major elements of subjectivity. Nevertheless, movable-bed tidal models can provide, for reasonable expenditure of effort, invaluable information that can be used by experienced engineers in forecasting the performance of works designed to alleviate coastal zone problems or improve harbor-inlet conditions. This balance between required results and justifiable effort generally

has been arrived at on the basis of subjective evaluation of the desired end product, the impacts and potential costs of inaccuracies, and the magnitude of the problem being addressed.

Over the past several decades steadily increasing dependence has been placed on movable-bed hydraulic models to guide the design and modification of coastal structures. It is somewhat surprising, therefore, that the question of conformity between model predictions and prototype behavior has received little attention. In the absence of such an assessment, there is little guidance available for determination of the reliability of model results. It is this "verification vacuum" which is largely responsible for the wide divergence of opinion--ranging from valueless to indispensible--concerning the usefulness of movable-bed tidal models. There are several obvious reasons that the question of model-prototype conformity has not received more critical attention. First among these is the cost and difficulty of obtaining prototype data that are sufficiently detailed for a meaningful evaluation of model predictions. Second, many of the prototypes performed satisfactorily and thus there was no compelling reason to obtain data on them which were adequate for evaluation of the model predictions. Third, in some cases the prototype modifications differed significantly from those tested in the model. Finally, there is the element of human nature that prefers uncertainty to unpleasant definitive answers.

2. Scope of the Study.

The principal objective of this study was to assess the reliability of movable-bed tidal inlet hydraulic models as predictors of prototype behavior, or, failing that, to determine the information needed for such an assessment. The investigation was pursued in the following stages:

(a) A literature review was made to determine the present understanding of and practice concerning similitude requirements for movable-bed coastal models.

(b) Model-based predictions were compared with prototype measurements to evaluate the accuracy of model calibration and the ability of movable-bed tidal inlet models to predict prototype performance.

(c) The major limitations and capabilities of movable-bed tidal inlet models were assessed.

Movable-bed model studies may be evaluated on the basis of how well they reproduce: (a) prototype patterns and rates of beach erosion and accretion, (b) beach profiles, (c) inlet-bed topography, and (d) channel erosion and deposition rates. The choice of criteria for judging model fidelity depends on the desired end product of the investigation, and may vary somewhat from model to model.

The adequacy and accuracy of the predictions of completed model studies were evaluated in the light of: (a) the criteria of similitude adopted; (b) the modeling techniques and bed materials used; (c) the experimental procedures followed; (d) the quality of the prototype data utilized in calibration and verification of the model; and (e) the problems encountered in the conduct of the study and the limitations inherent in the model. The major capabilities and limitations of movable-bed tidal inlet models deduced from these comparisons are discussed below, and an assessment of the general conditions under which tidal inlet models may be expected to yield reliable results are delineated.

The present investigation was restricted to model studies conducted in the United States and Canada. Although it was believed that movable-bed model studies of tidal inlets had been conducted during the past several years by several private, university, and government organizations in the United States and Canada (see App. A for a partial listing), it was found that model studies of the type of interest to this study had been conducted in North America only by the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, Mississippi. WES has conducted seven movable-bed model studies of tidal inlets. However, only in the cases of Galveston Harbor entrance (Simmons and Boland, 1969) and Masonboro Inlet (Hollyfield, 1976), were the designs investigated in the model studies constructed in the prototype; hence, the prototype data could not be directly compared with those obtained in the other five model studies. The Masonboro Inlet model study was conducted as part of the General Investigation of Tidal Inlets (GITI) program. Satisfactory calibration was not achieved in this model because of inadequate prototype data. A meaningful comparison of model and prototype data could be made only for Galveston Harbor entrance. For the remaining model investigations the prototype data used in the model calibration were compared with those from the model to evaluate the accuracy of the model calibration.

The present state-of-the-art concerning movable-bed coastal models is summarized in Section II. The model studies conducted by WES are reviewed briefly in Section III. In Section IV, the accuracy of the model calibrations are evaluated, and the results of the comparison of model and prototype data for the Galveston Harbor entrance are presented in Section V. The conclusions of the study are summarized in Section VI.

II. A REVIEW OF THE STATE-OF-THE-ART CONCERNING MOVABLE-BED TIDAL MODELS

1. General.

In a correctly designed and operated hydraulic model the ratio of any physical quantity (e.g., pressure or velocity) in the model to the same quantity at the corresponding location in the prototype will be constant; the constant is known as the scaling factor for that quantity.

The similitude requirements are the conditions which must be satisfied if the scaling factors are to be constant at all locations in the model and bear a certain relation to each other. These may be derived by writing the governing equations relevant to the phenomena acting in the model and prototype in dimensionless form, by dimensional analysis plus insight into the nature of physical processes involved, or from empirical relations.

Since it is generally not possible to reproduce in a hydraulic model all aspects of the problem under investigation, only the most important features of the flow being studied are reproduced. The absence of similitude among the processes of secondary importance produces so-called model scale effects which may or may not be significant. In recent years model users have attempted to reduce scale effects in movable-bed models by specifying more rigorously the similitude conditions which must be fulfilled for reasonable reproduction of sediment transport and bed evolution to be achieved, and by seeking to fulfill these through use of lightweight model sediments. The present state-of-the-art with respect to the similitude conditions for movable-bed coastal models is reviewed in the following sections.

2. Similitude Conditions--Why?

Is it always necessary to satisfy certain dynamic similitude conditions in a coastal movable-bed model? It is often possible to find by trial and error a combination of waves and currents in a model which will reproduce the known prototype-bed topography and sediment transport rate to a certain scale. Why not, then, use the empirical approach; i.e., the trial-and-error procedure? To answer this question, consider what Vernon-Harcourt (1892) reported long ago on movable-bed model technology. According to him, a model can be used successfully to predict the effects of proposed modifications if (a) the originally existing conditions can be reproduced in the model, and (b) when existing regulating works are placed in the model, the changes that were brought about by these works can be reproduced. The first of these conditions, i.e., the satisfactory reproduction of the originally existing conditions, may be obtained by using a suitable combination of waves and currents, determined by trial and error, in the model. However, there is no guarantee that satisfactory reproduction would be obtained using the same combination of waves and currents when the existing constructed works are placed in the model; i.e., that condition (b) will be satisfied. In other words, significant scale effects may be produced by geometrical, wave, or current distortion, as well as by failure to satisfy one or another scaling requirement (e.g., Reynolds scaling). This dilemma was encountered in a model study reported by Reinalda (1960), in which the model results were compared with the prototype data for the periods before and after construction of groins along the coast near Thyboron Channel on the west coast of Denmark. The horizontal and vertical scales of the model were 1:250 and 1:40, respectively. Ground Bakelite with mean diameter of 0.071 inch (1.8 millimeters) and a density of 84.3 pounds per cubic foot (1,350 kilograms

per cubic meter) was used as sediment. The waves and currents were reproduced according to the Froude law. The sedimentological time scale was determined by comparing the rates of coastline recession measured in model and prototype. Groins were built in the model at locations and times corresponding to those at which prototype groins had been installed. The relationship between the sedimentological time scales in the model and the prototype for the preconstruction and post-construction periods is shown in Figure 1. For the period from 1874 to 1890 (before the construction of groins) 1 year in prototype corresponds to 0.5 hour in the model; after 1920 (following installation of the groins) 1 year in prototype corresponds to 2 hours in the model. Therefore, on the basis of the time scale determined for the earlier period, the model underpredicted the effectiveness of the groins on the rate of recession of the shoreline by a factor of 4. Although the groins in the model reduced the rate of recession of the shoreline, as was observed also to be the case in the prototype, the field rate of sediment transport was not accurately reproduced in the model. In this model a scale effect clearly presented itself and produced phenomena in the model which caused its behavior to deviate significantly from that of the prototype.

It might have been possible to find another combination of waves and currents which would have yielded the same time scale for both the preconstruction and postconstruction periods (although the probability of doing so is very small). But such a trial-and-error procedure is very time consuming and expensive. It can be applied only in those cases in which extensive prototype data for both preconstruction and postconstruction periods are available; these instances are very rare. Usually, the model study is being conducted to investigate proposed prototype construction. Therefore, this empirical approach can be applied only in very few cases and with limited expectation of success. It follows that the realization of satisfactory model results can be achieved in most cases only by satisfying the necessary similitude conditions at the outset. As mentioned in Section I, the requirements of similitude in erodible-bed models still are not well defined. A certain amount of experimentation to determine the proper combination of waves and currents necessary to reproduce the prototype conditions satisfactorily and to calibrate each model to find the sedimentological time scale will likely be required even if the similitude requirements have been satisfied to the extent possible. But the refined procedure will certainly reduce the effort required for model calibration. Moreover, the results from properly scaled models can be used with more confidence.

3. Similitude Conditions.

Several reports on the similitude requirements for movable-bed coastal models have been written in the past decade (Bijker, 1967; Fan and Le Mehaute, 1969; Yalin, 1971; Migniot, 1972; Kamphuis, 1975). Dimensional analysis generally has been used to derive the dimensionless quantities which must assume equal values in the model and

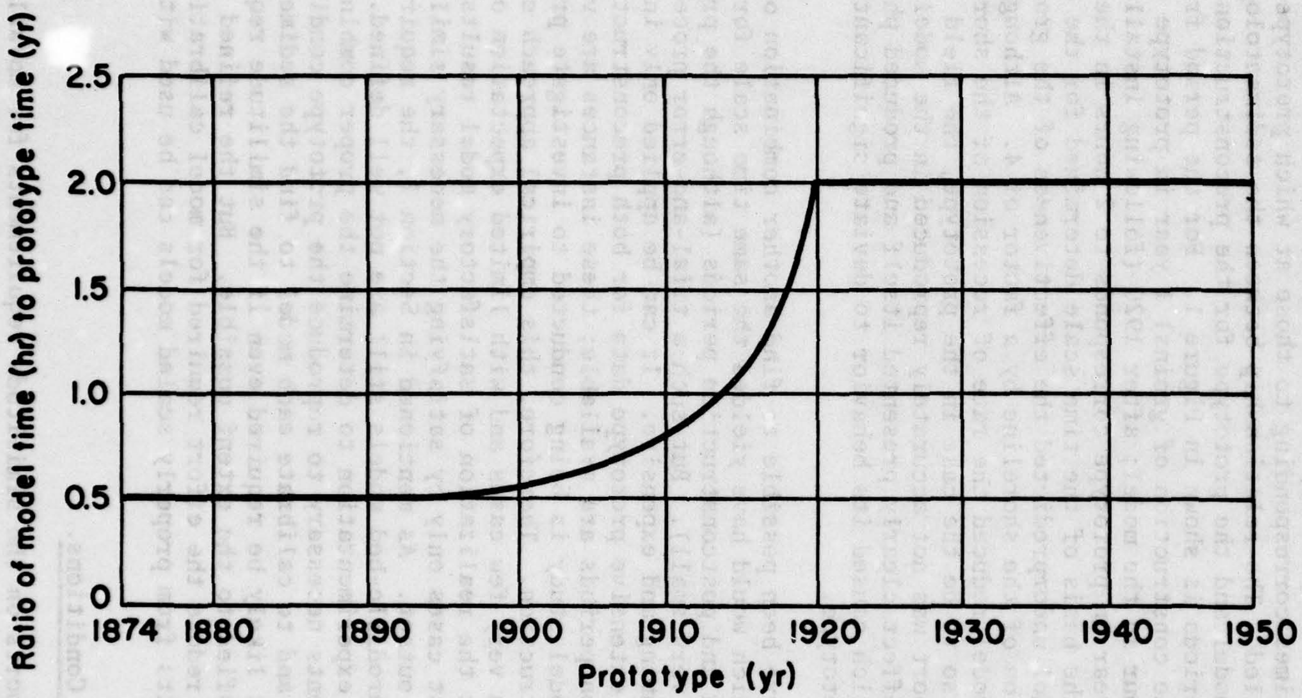

Figure 1. Variation in the model sedimentological time due to construction of groins.

prototype for similitude to attain. Any dependent property, A, of the flow (e.g., sediment transport rate, shoaling depth) may be expressed in terms of the independent variables by the following relationship:

$$A = f\,[H, L \text{ (or } T), \sigma_w, \theta, T_t, D, V, \rho, \nu, \rho_s, d, \sigma_g, X, g] \qquad (1)$$

where

H = wave height		
L = wavelength		
T = wave period		Wave parameters
σ_w = parameter which describes the distribution of wave heights and periods		
θ = wave direction		
T_t = tidal period		
D = representative fluid depth		Tide and current parameters
V = current velocity		
ρ = density of water		Fluid parameters
ν = kinematic viscosity of water		
ρ_s = density of sediment particles		
d = diameter of sediment particles		Sediment parameters
σ_g = parameter which describes the size distribution of sediment particles		
X = characteristic horizontal dimension (in distorted models)		
g = gravitational constant		

Equation (1) may be expressed in dimensionless form as

$$\pi_A = \phi_A \left\{ \frac{H}{D}, \frac{L}{D} \left(\text{or } \frac{T^2 g}{D} \right), \sigma_w, \theta, \frac{T_t V}{X}, \frac{V^2}{gD}, \frac{VD}{\nu}, \frac{\rho_s}{\rho}, \frac{d}{D}, \sigma_g, \frac{D}{X} \right\} \qquad (2)$$

where π_A is the dimensionless dependent variable. Equation (2) is so general that it is of little practical use without modification. Moreover, the dimensionless parameters given in equation (2) are not unique;

it is possible, at least in principle, to express them in a number of alternate forms. The most appropriate forms of the parameters can not be based on dimensional analysis alone, but must be guided by consideration of the physical processes involved. Moreover, it is neither essential nor practical to have the values of all dimensionless quantities equal in model and prototype. Equality generally can be attained only among the more important dimensionless variables in a practical model. Nonequality of the remaining ones will lead to model scale effects which should be kept to a minimum. Note that in a movable-bed hydraulic model the motions of both the fluid (waves, tides, and currents) and the bed material (sediment transport and formation of bed topography) must be simulated.

a. Similitude of Waves, Tides, and Currents. The phenomena of waves, tides, and currents are dominated by inertia, gravity, and friction forces; therefore, their similitude requires scaling by the Froude law, provided the bed configurations on which the friction forces depend are properly reproduced. However, the correct simulation of sediment motion, as discussed in the next section, may require a deviation of the fluid motion from that required by Froude scaling.

There are several concepts regarding adjustment or "distortion" of waves, tides, and currents in models to obtain better reproduction of the bed evolution. These argue for distortion of wave motion only (Fan and Le Mehaute, 1969); exaggeration of currents and tides only (Kamphius, 1975); modification of waves, tides, and currents (Bijker, 1969); or reduction of the wave period without distortion of the wave amplitude or exaggeration of the tides and currents (F. Abecasis, personal communication, Laboratorio Nacional de Engenharia Civil, Lisbon, Portugal, 1976). Fan and Le Mehaute (1969) advocate the distortion of waves only in models with large distortion ratios (ratio of vertical to horizontal geometric scales), in which wave breaking is not correctly reproduced. There appears to be general accord that the waves should be scaled according to the Froude law, with the scales for wavelength and wave height (the first two quantities on the right-hand side of eq. 2) equal to the vertical geometric scale (Yalin, 1971; Migniot, 1972; Kamphius, 1975). This condition ensures proper wave breaking and refraction in the model (provided the model-bottom topography is correctly modeled), but wave reflection and diffraction are not reproduced correctly (because the wavelength is not scaled according to the horizontal length scale). Both wave refraction and diffraction can be simulated correctly only in an undistorted model.

The parameters σ and θ in equation (2) can be simulated satisfactorily in the model if the wave machine produces a continuous succession of regular wave groups of different heights, periods, and directions (referred to herein as irregular waves) to reproduce the prototype waves. The use of irregular waves in the model has been practiced since 1948 by the Laboratoirie Central d'Hydraulique de France (Migniot, Orgeron, and Biesel, 1975). The Laboratorio Nacional de Engenharia Civil, Lisbon, Portugal, also employs a wavemaker with these

capabilities (F. Abecasis, personal communication, 1976). How critical is the use of "irregular" waves in the model? A large percentage of sediment transport occurs during the passage of high waves, which occur during only a small fraction of the time; the average or low waves, which prevail a larger fraction of the time, move only a small part of the transported sediment. Therefore, the yearly storms in the model should be reproduced to the extent possible. In fact, reproduction of the "wave climate" in the model is judged to be of prime importance to the successful outcome of a movable-bed model study.

As previously mentioned, the tides and currents normally should be simulated according to the Froude law. But the correct simulation of the sediment motion, as discussed in the following section, may require a certain exaggeration of the current velocity and tidal period. Therefore, the simulation of the dimensionless parameters $T_t V/X$ and V^2/gD in equation (2) will be discussed later. It still remains to simulate (or to prove negligible) four remaining dimensionless parameters in equation (2); Reynolds number, $R = VD/\nu$; density ratio, ρ_s/ρ; the parameter describing the size distribution of sediment particles, σ_g; and the ratio of sediment size to flow depth, d/D; and to account for effects of model distortion, D/X. The correct form of these dimensionless parameters will be derived from the similitude conditions for the sediment motion.

b. Similitude of Sediment Motion. Froude similitude permits dynamically scaled representation of the fluid motion in the model (provided viscous effects play only a minor role in model and prototype), but does not take into consideration the motion of the sediment. In order to define a suitable model-bed material (sediment diameter, d, and density, ρ_s) and a model distortion, D/X, which will reproduce sediment in the model in a way that is dynamically similar to that in the prototype, the ways in which the various sediment transport quantities (e.g., transport rate, bed topography evolution) are related to the dimensionless variables in equation (2) were examined.

For the satisfactory simulation of sediment motion and bottom evolution in a movable-bed tidal model, the following conditions should be satisfied:

(a) The incipient sediment motion of the sediment correctly simulated.

(b) The rate of sediment transport reproduced to the correct scale.

(c) The shape of the beach reproduced to the correct scale.

Unfortunately, the relationships among the various dimensionless variables which define these conditions are not well formulated. Past investigators have used different relations and as a result have

proposed different similitude conditions; these are summarized in a report by Kamphuis (1975). The following discussion is based on the present state of knowledge concerning the roles of the conditions stated above.

(1) Incipient Entrainment of Sediment. In order that the areas of scour and shoaling in the model be similar to those in the prototype, the condition of initiation of sediment motion should be correctly simulated. Only very limited experimental data are available on initiation of sediment motion by the combined action of waves and currents. The condition for initiation of motion of a cohesionless material in a unidirectional flow is given by the Shields criterion (Vanoni, 1975), which graphically relates the critical shear stress or shear velocity for incipient motion to the sediment and fluid properties. Madsen and Grant (1976) showed that the Shields criterion for the initiation of sediment movement by unidirectional flow is also a quite accurate and general predictor for initiation of sediment motion by oscillatory flow. This observation suggests that the initiation of sediment motion by both waves and currents can be formulated in terms of the Shields parameters. Therefore, the criterion for the incipient movement of sediment under the action of waves and currents will be expressed as

$$F_* = f_1(R_*) \tag{3}$$

in which

$$R_* = \frac{V_* D}{\nu} \tag{4}$$

and

$$F_* = \frac{V_*}{\sqrt{g\gamma' d}} \tag{5}$$

where V_* is the shear velocity based on total shear stress due to both waves and currents; $\gamma' = (\gamma_s - \gamma)/\gamma$ is the normalized apparent specific weight of the submerged sediment; and γ and γ_s are the specific weights of the fluid and sediment, respectively. Both F_* and R_* are based on shear velocity, V_*, which is a dependent variable. The Shields criterion can be expressed in a modified form (Task Committee on Sedimentation, 1966), as

$$F_* = f_2(G) \tag{6}$$

where $G = \gamma' g d^3/\nu^2$ is obtained by dividing R_*^2 by F_*. Valembois (1960) modified the Shields criterion and expressed G as a function of R_*; he referred to G as the grain parameter. For the simulation of incipient entrainment of sediment, the model and prototype values of the grain parameter, G, and particle Froude number, F_*, should be equal. This gives the following similitude conditions:

$$\lambda_{\gamma'}\lambda_d^3 = \lambda_\nu^2 \tag{7}$$

and

$$(\lambda_{V_*})^2 = \lambda_{\gamma'}\lambda_d \tag{8}$$

where λ represents the scaling factor [(model value)/(prototype value)] for the quantity symbolized by its suffix. It is assumed that λ_g is unity. It should also be pointed out that if the values of F_* and G are equal in model and prototype, then the value of R_* also is equal in both.

(2) Sediment Transport Rate. Experimental data on the sediment transport rate produced by the combined action of waves and currents are also very limited. A recent analysis of laboratory data on sediment transport due to unidirectional and oscillatory flows acting separately (Madsen and Grant, 1976) indicates that the sediment transport rate in both cases can be expressed by relationships of the form

$$\phi = f_3(\Psi) \tag{9}$$

in which

$$\phi = \frac{q_s}{d\sqrt{\gamma' g d}}$$

and

$$\Psi = \frac{V_*}{\sqrt{\gamma' g d}} \equiv F_*$$

where q_s is the volumetric sediment transport rate per unit width. Lin (1972) conducted some tests in a model basin to study sediment transport by inlet currents and waves approaching the beach at an angle of 10°. He used dimensional analysis to derive a framework for presentation of his experimental results and expressed the sediment transport rate as a function of Froude number, bottom shear stress, friction factor, and wave steepness. Bijker's (1967) experimental study on sediment transport due to currents and waves led him to express the sediment transport rate by the relation

$$\frac{q_s}{V_{*c}d} = 1.95 \exp\left[-0.33\frac{\gamma' g d}{\mu V_*^2}\right] \tag{10}$$

where V_{*c} is the shear velocity based on current shear only and μ is a "ripple factor." Equations (9) and (10) are similar except for the inclusion of the ripple factor in equation (10). If $\lambda\mu \simeq 1$ is adopted, as was found by Bijker (1967), the same similitude condition is obtained from equations (9) and (10); i.e., the model and prototype

values of F_* should be equal. This is the condition given by equation (8). The shear velocity scale in equation (8) can be written

$$\lambda_{V_*} = \lambda_{V_t} / \lambda_C \tag{11}$$

where V_t is the resultant velocity due to currents and waves and C is a bed-resistance coefficient of the Chezy or Darcy-Weisbach type. The scaling law for the resultant velocity, V_t, can be obtained from equations (8) and (11) as

$$\lambda_{V_t} = (\lambda_{\gamma'} \lambda_d)^{1/2} \lambda_C \ . \tag{12}$$

It is proposed here that the scale for the current velocity be that given by equation (12); i.e.,

$$\lambda_V = (\lambda_{\gamma'} \lambda_d)^{1/2} \lambda_C \ . \tag{13}$$

The quantity λ_C cannot easily be predicted because it is heavily dependent on the bed configuration, which is also a dependent variable. In the absence of better information, λ_C can be assumed to be $\sqrt{\lambda_X / \lambda_Y}$, where λ_Y is the vertical dimension scale; this is the value yielded by the Froude law and the Chezy equation. For correct simulation of the initiation of sediment motion and of the sediment transport, the model-bed material should satisfy the similitude condition given by equation (7) and the current velocities should be scaled according to equation (13).

(3) Equilibrium Beach Profiles. The similitude conditions for simulation of the sediment motion do not impose any constraint on the value of model distortion. In order to conserve the general beach shape, the ratio of model beach slope to the beach slope of the prototype should be equal to the model distortion (Bijker, 1967). Several investigations have been performed in recent years to relate parameters describing the shapes of beach profiles to those characterizing the bottom sediment and incident wave characteristics (Nayak, 1970; Noda, 1972; Paul, 1972). Other investigators have proposed empirical relations for beach profiles in the surf zone (Larras, 1961), in the foreshore zone (Sitarz, 1963), and for the offshore region (Eagleson, Glenne, and Dracup, 1963). A generally acceptable relationship which describes the equilibrium beach profile in all zones in terms of the relevant independent variables is not available at present. It is recommended that until a reliable predictor for equilibrium beach profiles is developed, the following procedure be adopted (Fan and Le Mehaute, 1969). For each model study, some preliminary experiments in a two-dimensional wave tank should be conducted using the selected model-bed material, vertical scale, offshore depth, and characteristic model wave conditions (Froude-scaled using the vertical scale). The beach profile obtained in the two-dimensional wave tank should be

compared with the corresponding prototype beach profile to determine the actual model distortion ratio. If the ratio does not agree with that selected for the investigation in the three-dimensional tank, the distortion and the bed material should be adjusted until the values are in satisfactory agreement. Experiments should be conducted for both summer and winter beach profiles. It is realized that it is not possible to reproduce the entire beach profile. Since the profiles in the foreshore and the surf zone are generally of primary importance, the deviations in the profile of the offshore region usually can be regarded as an unavoidable model scale effect.

Thus far, the effects of the size distribution of sediment particles, σ_g, on the sediment motion have not been discussed. It is possible to reproduce the prototype sediment-size distribution in the model material (by a sieving process). However, the effects of size distribution on sediment motion are normally disregarded, and usually no effort is made to reproduce the prototype-size distribution. However, the use of model-bed materials which have strongly bimodal or very narrow unimodal size distributions should be avoided (Collins and Chesnutt, 1975).

4. Summary of Similitude Conditions.

On the basis of the foregoing discussion, the following similitude conditions are proposed for movable-bed coastal model studies:

(a) The waves should be scaled according to the Froude law, with the scale for wavelength and wave height equal to the vertical geometric scale; i.e.,

$$\lambda_H = \lambda_L = \lambda_Y \tag{14}$$

and

$$\lambda_T = \lambda_Y^{1/2} \tag{15}$$

The use of a wave machine capable of producing irregular waves is recommended so that yearly storms and irregular waves can be simulated in the model.

(b) The model-bed material should satisfy

$$\lambda_{\gamma'} \lambda_d^{\,3} = \lambda_\nu^{\,2} . \tag{16}$$

(c) The current velocity should be scaled according to

$$\lambda_V = (\lambda_{\gamma'} \lambda_d)^{1/2} \lambda_C . \tag{17}$$

The value of λ_C appearing in equation (17) cannot be predicted easily, and, in the absence of better information, may be taken to be $(\lambda_X/\lambda_Y)^{1/2}$.

(d) The permissible model distortion should be determined from the results of two-dimensional undistorted wave tank experiments performed to determine equilibrium beach profiles.

Constraints on successful application of these proposed similitude conditions include:

(a) The model sediment size and density derived from equation (16) must be such that practical model operation is feasible. For example, sediment that is too light is easily disturbed during model filling, draining, and sounding of the model bed, and should be avoided.

(b) Deviation from Froude similarity resulting from use of equation (17) must be carefully examined to avoid excessive distortion of hydrodynamic behavior of the model.

(c) Permissible scale distortion for proper reproduction of beach profiles may not correspond to proper scale distortion for reproduction of longshore sediment transport or inlet behavior.

III. SUMMARY OF MOVABLE-BED TIDAL MODEL STUDIES CONDUCTED BY WES

1. General.

WES has conducted movable-bed model studies of seven tidal inlets. Brief backgrounds on each of these inlets and the objectives of the model studies follow.

a. Absecon Inlet, New Jersey (U.S. Army, Corps of Engineers, 1943). Absecon Inlet is located on the New Jersey coast between Brigantine and Atlantic City beaches, and connects the Atlantic Ocean with Absecon and Reed Bays, and with the harbor and yacht basin of Atlantic City. The purpose of the model study, which began in 1939, was to determine the effectiveness of the different proposed jetty plans at the entrance of Absecon Inlet in reducing maintenance dredging in the navigation channel, and the effects of the jetties on the stability of the Atlantic City beach.

b. Barnegat Inlet, New Jersey (Sager and Hollyfield, 1974). Barnegat Inlet lies on the New Jersey coast approximately 50 miles (80.5 kilometers) south of Sandy Hook and 32 miles (51.5 kilometers) north of Atlantic City. It is the principal connection between the Atlantic Ocean and Barnegat Bay. The navigation channel through the inlet was protected by two converging stone jetties which were completed in September 1940. These two jetties failed to maintain a stable navigation channel. The objective of this model study, which began in 1968, was to evaluate the effectiveness of several alternate plans in establishing and maintaining a stable navigation channel.

c. Fire Island Inlet, New York (Bobb and Boland, 1969). Fire Island Inlet is located on the south shore of Suffolk County, Long Island, New York, and is the primary waterway for boat traffic between Atlantic Ocean and Great South Bay. This model study was started in 1965 and was undertaken to evaluate the design of a proposed littoral drift trap and rehandling basin, connecting channel, and training dike, and to determine if a jetty or other structure was required to maintain a stable navigation channel.

d. Galveston Harbor Entrance, Texas (Simmons and Boland, 1969). Galveston Bay is in the southeastern part of Texas on the Gulf of Mexico, approximately 60 miles (96.5 kilometers) west of Port Arthur and 50 miles south of Houston. The north and south sides of the entrance channel are protected by stone jetties about 5 and 7 miles (8 and 11.3 kilometers) long, respectively. This model study was initiated in 1965 to seek a means of protecting the north jetty from undermining that was threatening its stability, determining an alinement for the navigation channel that would not experience unacceptable shoaling rates, and describing the shoaling characteristics of a deepened channel with the new alinement.

e. Lynnhaven Inlet, Virginia (U.S. Army, Corps of Engineers, 1952). Lynnhaven Inlet is located on the south shore of Chesapeake Bay 5 miles west of Cape Henry and 11 miles (17.7 kilometers) east of Norfolk, Virginia. The objectives of the model study, which began in 1945, were to determine the effectiveness of jetties in preventing shoaling of the navigation channel and to predict effects of jetties on adjacent beaches.

f. Masonboro Inlet, North Carolina (Hollyfield, 1976). Masonboro Inlet, on the Atlantic coast near Wilmington, North Carolina, separates Wrightsville Beach to the north from Masonboro beach to the south. This model study, which was begun in 1969 as part of the GITI program, was conducted to evaluate the reliability of movable-bed hydraulic model predictions of inlet response to a major improvement project.

g. Moriches Inlet (no reference available). No formal report on Moriches Inlet was published. This inlet was found to be unstable and the model study apparently did not yield any significant results.

All of the models had some areas of fixed bed and some that were movable, and all were operated with tides and waves. With the exception of the Masonboro Inlet investigation, each study was conducted to solve a particular problem.

The following general procedure was adopted in the selection of the geometric scales and in the calibration (referred to as verification in the WES reports) of these models. (The term calibration is used here to refer to the procedure of adjusting model parameters until the model can reproduce some phase of measured prototype behavior; verification refers to the procedure in which the model behavior is checked against

prototype data not used in the calibration tests.) The maximum horizontal scale that could be fitted into the available space was adopted and the vertical scale which would give a model distortion of five was used. Two earlier prototype hydrographic surveys were selected and the movable bed of the model was molded to conform to the earlier one. Model calibration consisted of initially operating the model with Froude-scaled prototype waves and tides. Based on the results of this trial calibration test, selected test parameters (including tidal heights in the ocean and bay, wave directions, wave periods, wave heights, sequences of wave period and wave direction, and rate of sand feeding of adjacent beaches) were varied in subsequent tests until a satisfactory reproduction of the second set of prototype bed topography data was achieved and maintenance dredging volumes for the model navigation channel were in general agreement with prototype values. No quantitative or well-defined qualitative similitude requirements were imposed. The model calibration was not verified in any of these studies because sufficient prototype data were not available.

2. Geometric Scales and Distortion.

The values of horizontal and vertical scales and the corresponding model distortions adopted in the WES model studies are listed in Table 1.

Table 1. Horizontal and vertical scales and model distortions employed in movable-bed tidal inlet model studies conducted by WES.

Inlet model study	Horizontal scale ($1/\lambda_X$)	Vertical scale ($1/\lambda_Y$)	Model distortion (λ_Y/λ_X)
Absecon	500	100	5
Barnegat	300	60	5
Fire Island	500	100	5
Galveston Harbor	500	100	5
Lynnhaven	400	80	5
Masonboro	300	60	5

The horizontal scale was selected such that the model could be accommodated in the available space, and a distortion ratio of five was adopted, i.e.,

$$\lambda_Y = 5\lambda_X \; . \tag{18}$$

No generally accepted criterion presently is available to guide selection of a distortion ratio. It is assumed that a small river flowing in its own alluvium is a distorted model of a large river (Le Mehaute, 1976), then the horizontal and vertical scales can be related by the Lacey equation,

$$\lambda_X = \lambda_Y^{3/2} \tag{19}$$

The scales λ_X and λ_Y of some movable-bed coastal model studies conducted by laboratories other than WES are plotted in Figure 2. As shown in the figure, the model studies conducted at WES, as well as those by most other investigators, had smaller vertical scales than given by equation (19).

Figure 3 shows a comparison of model and prototype beach profiles for range 17 of Absecon Inlet. The reproduction of beach profile in the model could hardly be considered satisfactory. The deviations between model and prototype beach elevations were as much as 7 feet (2.13 meters); this is about one-third of the total bed elevation change over a distance of nearly 1 mile (1.61 kilometers). The model and prototype beach profiles for other ranges also were compared, and found generally to be in no better conformity than those shown in Figure 3. It is not possible from the reported data to determine the exact factors responsible for the disparity between model and prototype beach profiles. In retrospect, however, it appears that other distortions or bed materials should have been examined to obtain better conformity between model and prototype profiles.

3. Prototype and Model Sediment Characteristics.

The properties of the sediments used in the WES model studies are summarized in Table 2. Sands with median diameters ranging from 0.18 to 0.25 millimeter were used as the bed materials in all models except that of the Galveston Harbor entrance, in which coal with a specific gravity of 1.4 and a median diameter of 1.4 millimeters was utilized. WES experienced some operating difficulties in using coal as model-bed material, including ripple formation and caving of the bed during draining of the model. European laboratories commonly use lightweight materials such as Bakelite, polystyrene resins, etc., for model-bed material. McNair (1976) evaluated model-bed materials under the GITI program; however, he investigated only sands and no definite conclusions were reported.

Table 2. Characteristics of prototype and model sediment.

Inlet model study	Model			Prototype		
	Size (mm)	Specific gravity	Material	Size (mm)	Specific gravity	Material
Absecon	0.18	2.70	Sand	0.30	----[1]	Sand
Barnegat	0.20[2]	2.65[2]	Sand	----[1]	----[1]	Sand
Fire Island	0.25	2.65	Sand	0.25	----[1]	Sand
Galveston Harbor	1.40	1.40	Coal	0.12 to 0.15	2.63 to 2.69	Sand
Lynnhaven	0.20	2.65[2]	Sand	----[1]	----[1]	Sand
Masonboro	0.25	2.65	Sand	0.19 to 0.25	2.65	Sand

[1]No information available.
[2]Approximate values.

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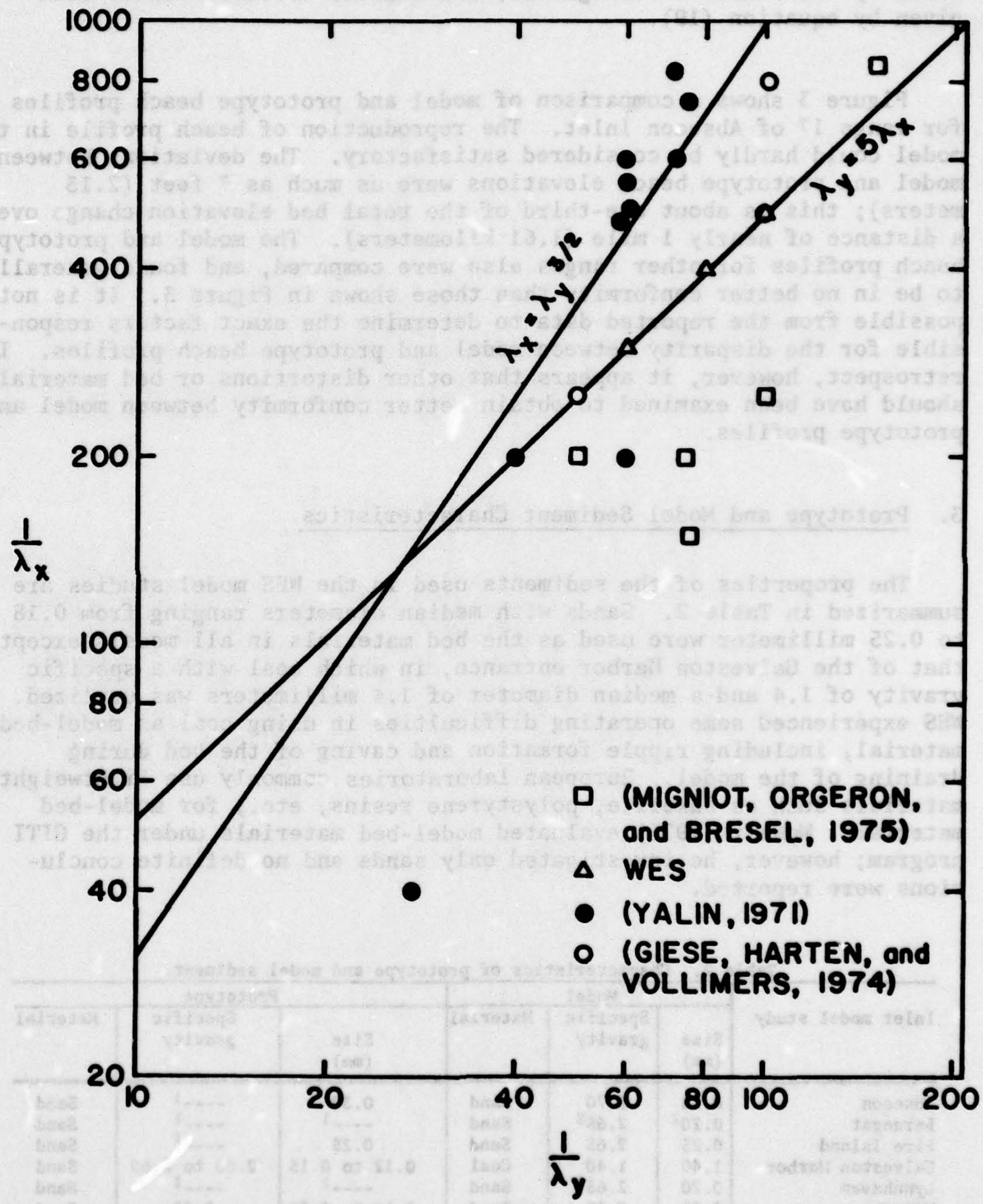

Figure 2. Relationship between the vertical and horizontal scales adopted in movable-bed coastal model studies conducted by WES and other laboratories.

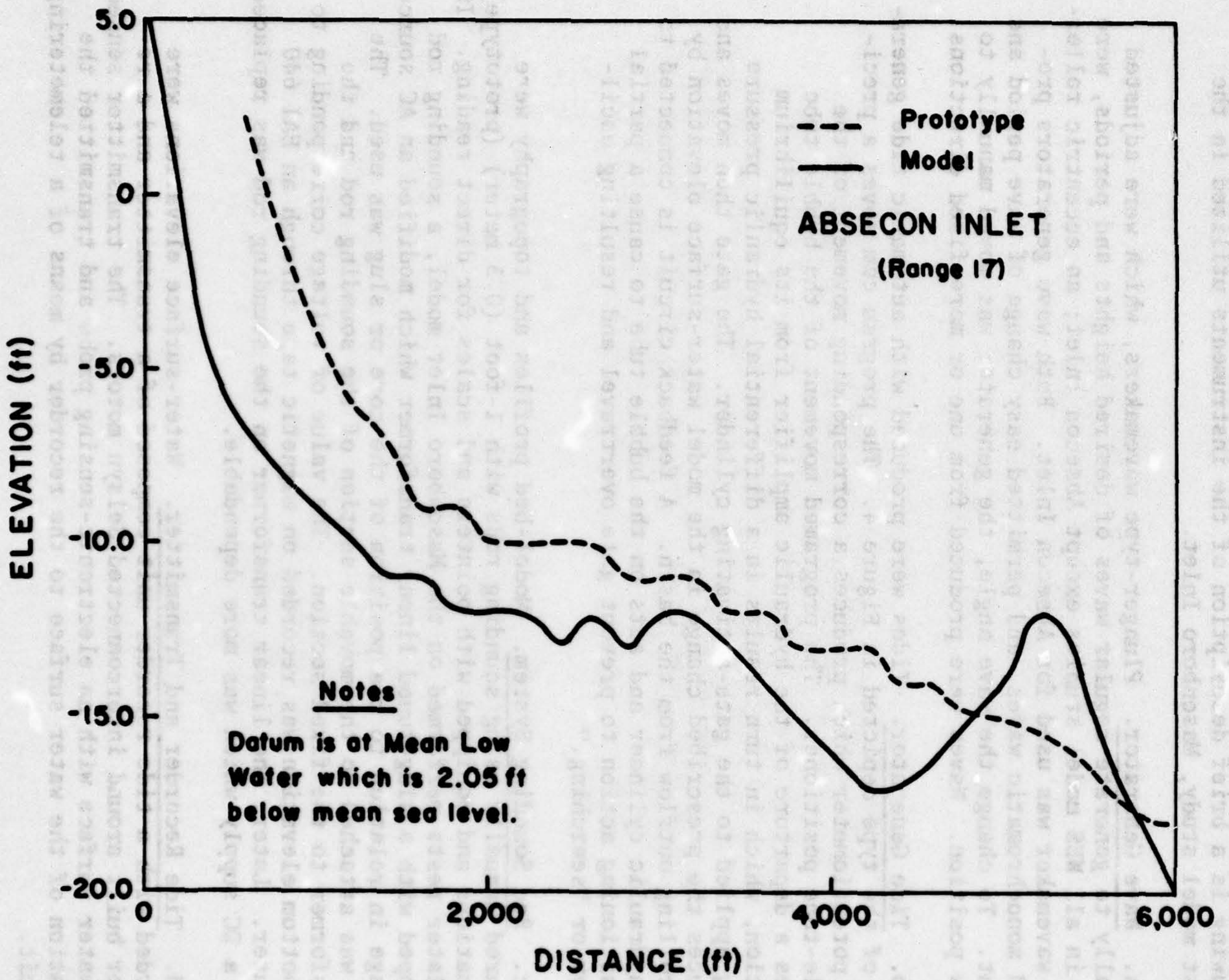

Figure 3. Comparison of model and prototype beach profiles at range 17 of the Absecon Inlet model.

4. Appurtenant Apparatus.

The equipment used for generating waves and tides and the instrumentation utilized for recording tides, wave heights, and bed configurations were practically the same for all the WES model studies. The following is a brief description of the instruments utilized in the latest model study, Masonboro Inlet.

a. Wave Generator. Plunger-type wavemakers, which were adjusted manually to generate regular waves of desired heights and periods, were used in all WES model studies except Absecon Inlet; an eccentric roller-type wavemaker was used for Absecon Inlet. Both wave generators produced monochromatic waves, and permitted easy change of wave period and height. To change the wave angle, the generator was moved manually to a new position. Waves were produced from one or more fixed directions.

b. Tide Generator. Tides were produced with automatic tide generators of the type depicted in Figure 4. The program cam moves a precision potentiometer which produces a corresponding movement of the bubble-tube positioner. The programed movement of the bubble tube causes a departure of the hydraulic amplifier from its equilibrium position, which in turn results in a differential hydraulic pressure being applied to the gate-activating cylinder. The gate then moves and produces the prescribed change in the model water-surface elevation by controlling outflow from the basin. A feedback circuit is connected to the hydraulic cylinder and acts on the bubble tube to cause a partial repositioning action to prevent gate overtravel and resulting oscillation or "searching."

c. Bed Sounding System. Model-bed profiles and topography were measured manually using sounding rods with 1-foot (0.3 meter) (prototype) graduations and equipped with pointers and scales for direct reading. In the later tests performed on the Masonboro Inlet model, a sounding rod equipped with a slug-tuned linear transformer which modified an AC source voltage in relation to the position of the core or slug was used. The core was attached to the movable section of the sounding rod and the transformer to the fixed section. The value of voltage corresponding to the bottom elevation was recorded on magnetic tape through an EAI 640 computer. Later, the linear transformer on the sounding rod was replaced with a DC supply which was more dependable.

d. Tide Recorder and Transmitter. Water-surface elevations were recorded with a tide recorder unit composed of a transmitter and a recorder built around interconnected Selsyn motors. The transmitter sensed the water surface with an electronic-sensing probe and transmitted the elevation of the water surface to the recorder by means of a telemetering circuit.

e. Wave Height Recordings. Conventional point gages were used to measure wave heights. The difference between the averages of several readings of elevations of wave crests and troughs was taken as the wave

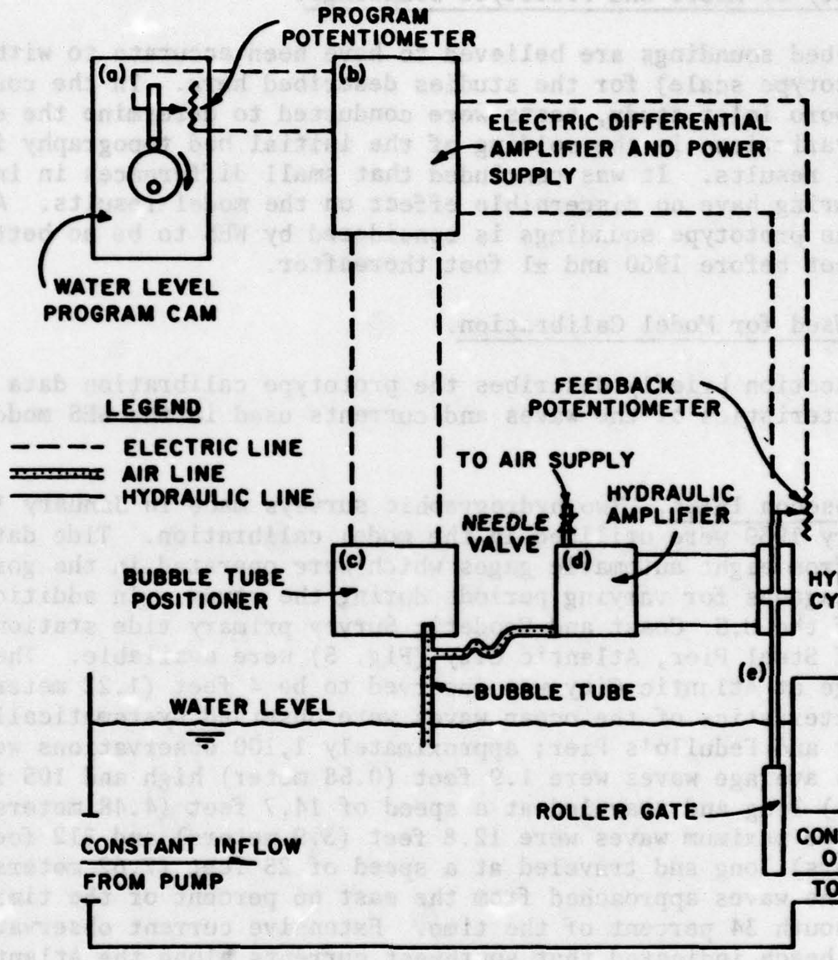

Figure 4. Schematic of the automatic tide generator and control system used in the WES model studies.

height at the gage location. An automatic continuous wave recording device was developed during the testing program with the Masonboro Inlet model and used in the later tests. Two Leopold and Stevens water-surface elevation transmitters were modified to measure wave crest and trough elevations.

5. Accuracy of Model and Prototype Soundings.

Model-bed soundings are believed to have been accurate to within ±1 foot (prototype scale) for the studies described here. In the course of the Masonboro Inlet study, tests were conducted to determine the effects of small variations in the molding of the initial bed topography in the model test results. It was concluded that small differences in initial bed contouring have no discernible effect on the model results. Accuracy of the prototype soundings is considered by WES to be no better than ±2 feet before 1960 and ±1 foot thereafter.

6. Data Used for Model Calibration.

This section briefly describes the prototype calibration data and the characteristics of the waves and currents used in the WES model studies.

a. Absecon Inlet. Two hydrographic surveys made in January 1936 and January 1939 were utilized in the model calibration. Tide data were obtained from eight automatic gages which were operated in the gorge and interior lagoons for varying periods during the study. In addition, the records of the U.S. Coast and Geodetic Survey primary tide station at the end of Steel Pier, Atlantic City (Fig. 5) were available. The mean tidal range at Atlantic City was observed to be 4 feet (1.22 meters). The characteristics of the ocean waves were observed systematically at Steel Pier and Fedullo's Pier; approximately 1,100 observations were made. The average waves were 1.9 feet (0.58 meter) high and 105 feet (32 meters) long and traveled at a speed of 14.7 feet (4.48 meters) per second. The maximum waves were 12.8 feet (3.9 meters) and 312 feet (95.1 meters) long and traveled at a speed of 25 feet (7.62 meters) per second. The waves approached from the east 66 percent of the time and from the south 34 percent of the time. Extensive current observations along the beach indicated that southwest currents along the Atlantic City beach occurred twice as often as northeast currents.

The tides imposed on the model by two identical, automatic tide generators reproduced the prototype mean tidal curves measured at Steel Pier and at Brigantine Bridge. The model inlet current velocity data for a station at Brigantine Bridge were in good agreement with the corresponding prototype data. The sequence of waves and the direction and velocity of littoral currents necessary to produce the January 1936 to January 1939 change in hydrography were arrived at through numerous trial experiments in the model (Table 3). Throughout the 3 years included in the calibration tests, the model Absecon channel was periodically dredged in accordance with the prototype dredging records. The

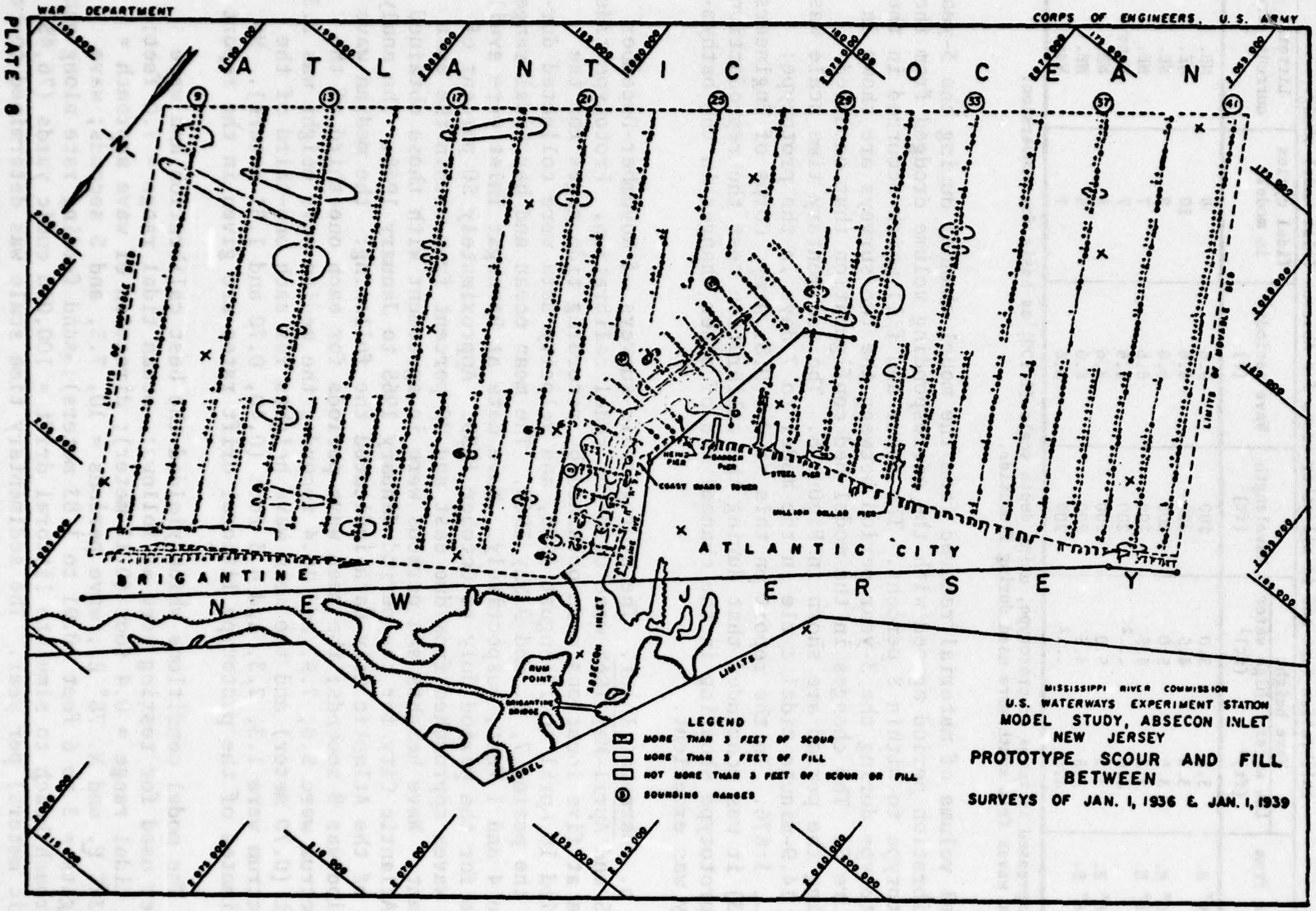

Figure 5. Prototype scour and fill in the Absecon Inlet.

Table 3. Sequence of hydraulic factors followed in each year of model operation, in calibration test and in all other tests for Absecon Inlet model study.

Waves from	Wave height: Low water (ft)[1]	Wave height: High water (ft)[1]	Wavelength (ft)[1]	Wave periods[1] (s)	Tidal cycles in models	Littoral currents from
S. 40° E.	3.5	5.0	200	8.6	8	NE.
E.	3.5	4.5	200	8.6	10	NE.
S. 40° E.	3.5	5.0	200	8.6	8	NE.
S. 60° E.	3.5	4.5	200	8.6	7	NE.
S.	4.0	---[2]	200	8.6	7	None
S. 40° E.	3.5	5.0	200	8.6	8	NE.
S. 60° E.	3.5	4.5	200	8.6	6	NE.
S.	4.0	---[2]	200	8.6	7	None

[1]Expressed in terms of prototype, using depth scale (1:100) as basis for conversion.
[2]No waves from south were used during floodtide.

total volume of material removed from the model channel during the 3-year calibration period agreed with the corresponding volume dredged from the prototype to within 8 percent. The scour and fill which occurred in the prototype during the 3-year period between the two surveys are shown in Figure 5. The changes in the model-bed configuration that occurred during the period are shown in Figure 6. The sedimentary time scale was one 14.9-minute tidal cycle in the model to 7 days in the prototype; i.e., 1:676. In the report on this study (U.S. Army, Corps of Engineers, 1943) it was concluded that during the calibration test the reproduction of prototype shoaling in the channel and of other changes in the bathymetry was excellent.

b. Barnegat Inlet. The hydrographic surveys of November-December 1965 and April-May 1968 were used for model calibration. Prototype tide data at five locations were obtained by recording tide gages for the period 18 April to 12 August 1968, and velocity data were collected during the period 7, 8, and 9 May 1968. The mean ocean and bay tidal ranges were 4 and 1 feet, respectively. Wave data at Barnegat Inlet were available for the period July to October 1939. Approximately 50 percent of the waves approached from due east and 90 percent from within the east octant. Wave heights and periods were in agreement with those obtained at Atlantic City for the period January 1965 to January 1968. The analysis of the Atlantic City data indicated the following: the median wave period was 8 seconds; the mean wave periods for each one-third of the spectrum were 5.0, 7.9, and 10.4 seconds; the median wave height was 2.3 feet (0.70 meter) and the mean wave heights for each one-third of the spectrum were 1.3, 2.3, and 4.3 feet (0.40, 0.70 and 1.31 meters). No estimates of the prototype littoral drift rates are given in the report.

The model conditions which yielded the best calibration and were later used for testing were as follows: ocean tidal range = 7.0 feet; bay tidal range = 0.4 foot (0.12 meter); direction of wave approach = S. 32° E. and N. 78° E.; wave periods = 10, 7.5, and 5 seconds; wave heights = 3 to 6 feet (0.91 to 1.83 meters); sand feeding rate along each approach beach to simulate littoral drift = 100,000 cubic yards (76,455 cubic meters) per year. The sedimentary time scale was determined to be 1:385 (96 model tidal cycles equal to 1 year prototype time). Maps

PLATE 10

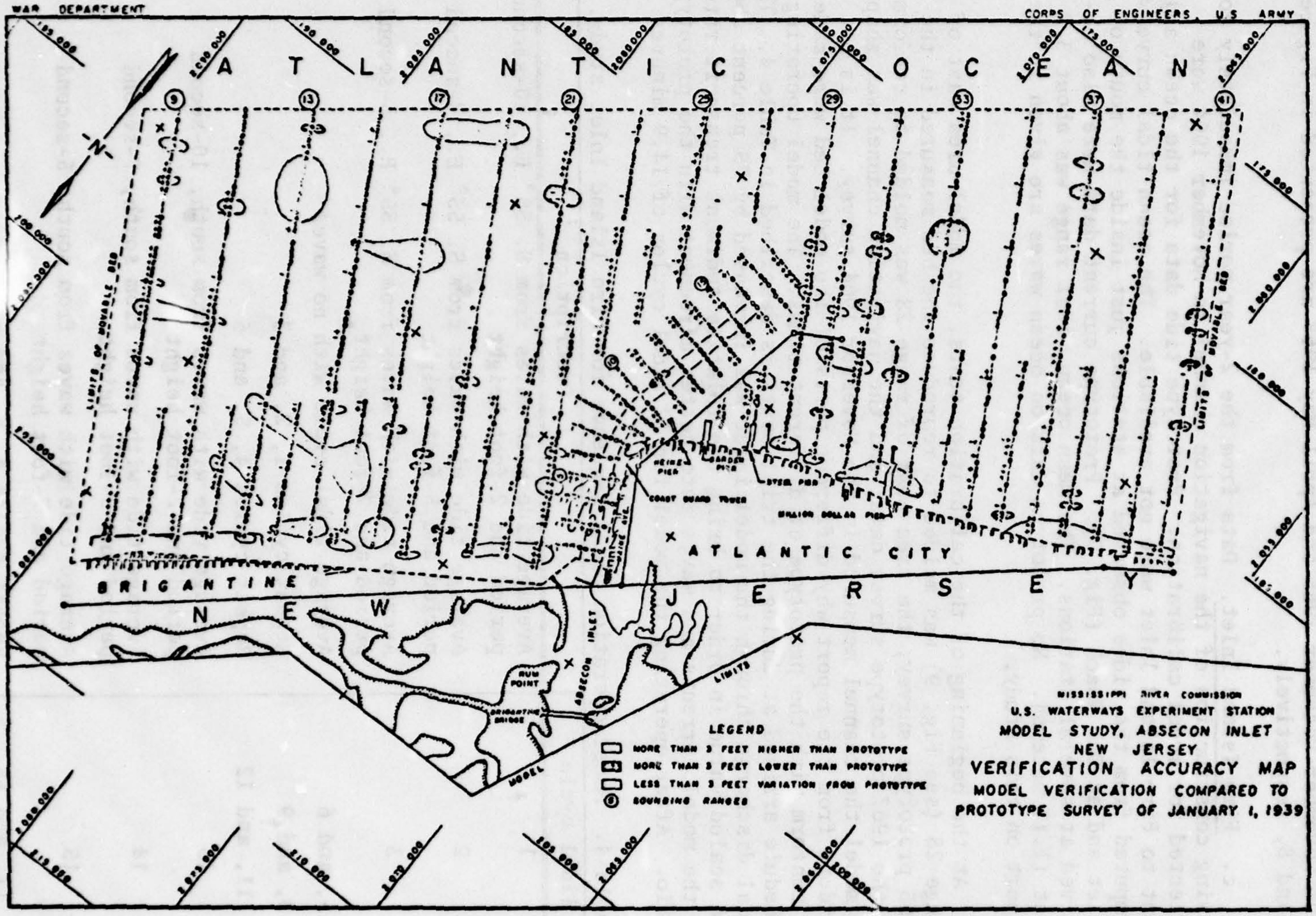

Figure 6. Model scour and fill in the Absecon Inlet.

showing the prototype and model scour and fill patterns during the period from November-December 1965 and April-May 1968 are presented in Figures 7 and 8, respectively.

c. Fire Island Inlet. Data from the 2-year period immediately following construction of the navigation channel in November 1964 were selected for model calibration. Prototype tide data for the ocean adjacent to Fire Island Inlet were not available. The ocean tidal curve was computed from the tides observed at stations just inside the mouth of the inlet and at Oak Beach (Fig. 9). Prototype current data were also observed at several stations. The mean ocean tidal range was about 3.7 feet (1.13 meters). No prototype data on ocean waves are given in the report on this study.

At the beginning of the calibration tests, the model area east of range 28 (see Fig. 9) was molded to reproduce the bed measured in the 1965 prototype survey; the area west of range 28 was molded to conform to the 1967 prototype survey data; and the navigation channel was shaped to model the channel measured in the November 1964 survey. It is not evident from the report why different parts of the model bed were made to conform with the prototype at different times. The model operating schedule arrived at during the trial tests is described in Table 4. The tidal discharge through the model inlet was increased by 75 percent above the scaled value in order to bring the relative sediment transport rates of the model currents and waves into better agreement with the prototype ratio. After operating the model for 72 tidal cycles of 14.9 minutes

Table 4. Model operation tidal sequence for Fire Island Inlet study.

Tidal cycle	Description
1	Average tide with waves from S. 55° E., 10-second period and 2-foot height
2	Average tide with waves from S. 55° E., 7-second period and 5-foot height
3	Average tide with waves from S. 55° E., 5-second period and 7-foot height
4, 5, and 6	Average tidal cycle with no waves
7, 8, and 9	Repeat cycles 1, 2, and 3
10, 11, and 12	Repeat cycles 4, 5, and 6
13	Average tide with waves from south, 10-second period and 2-foot height
14	Average tide with waves from south, 7-second period and 5-foot height
15	Average tide with waves from south, 5-second period and 7-foot height
16, 17, and 18	Repeat cycles 4, 5, and 6

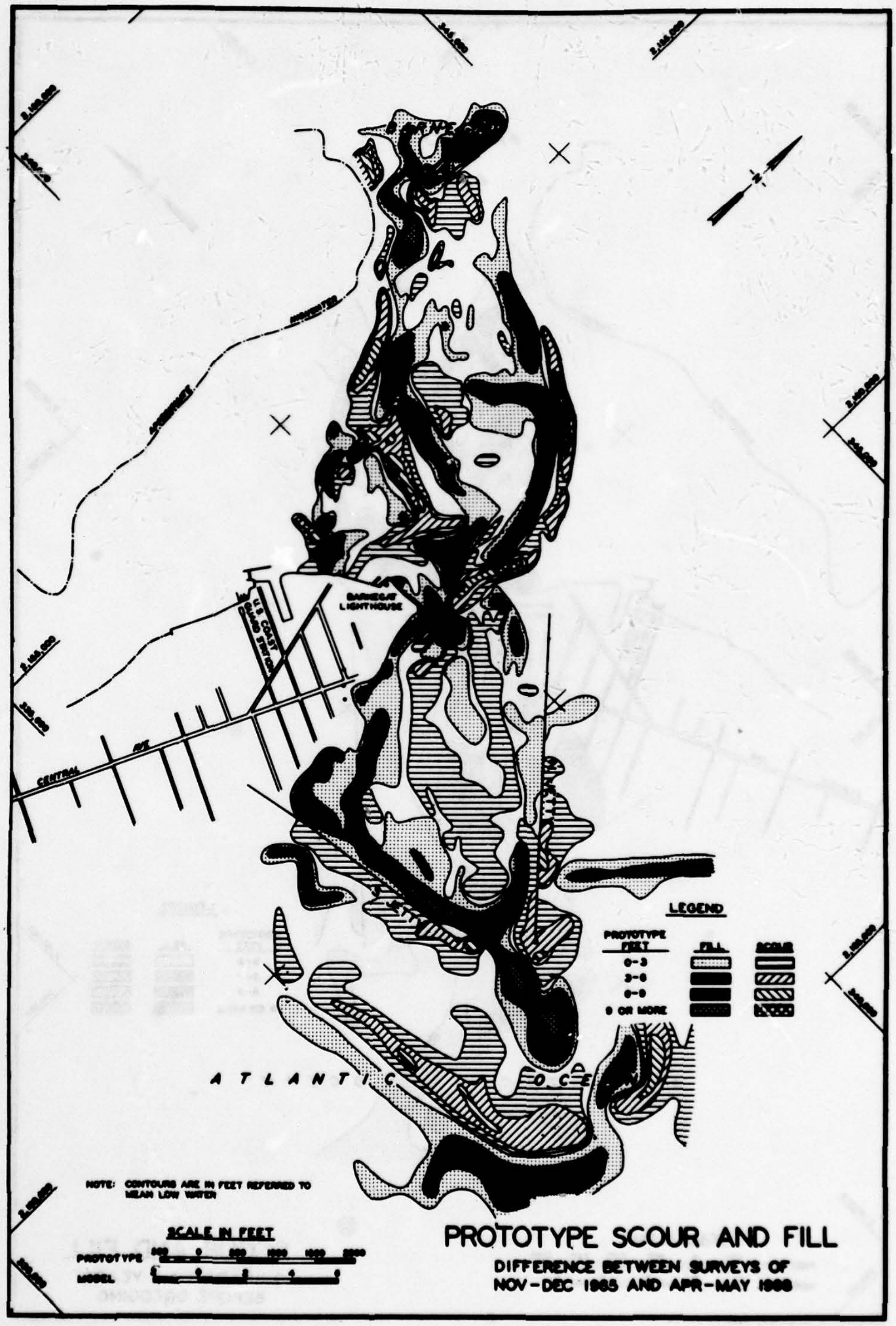

Figure 7. Prototype scour and fill in the Barnegat Inlet.

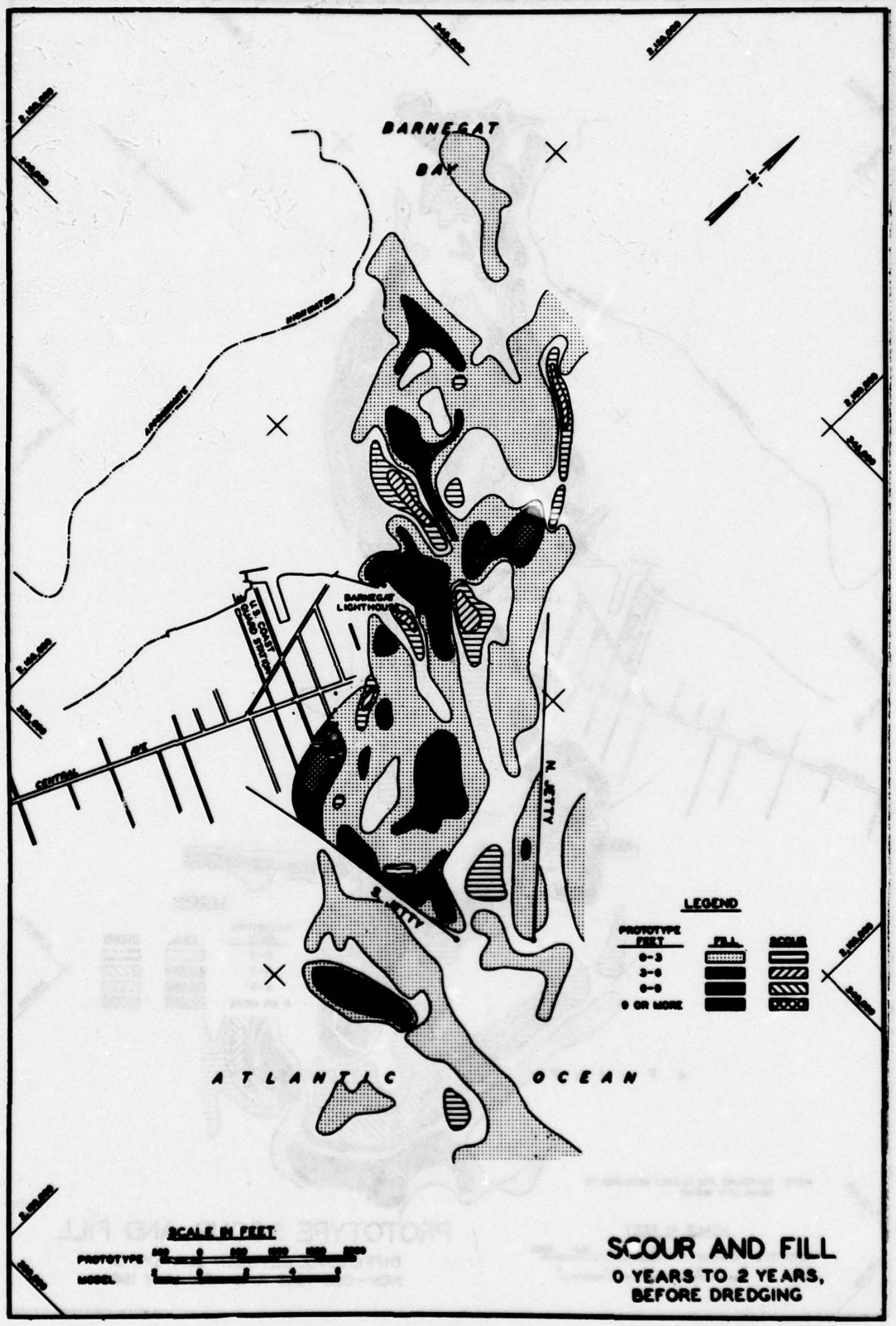

Figure 8. Model scour and fill in the Barnegat Inlet.

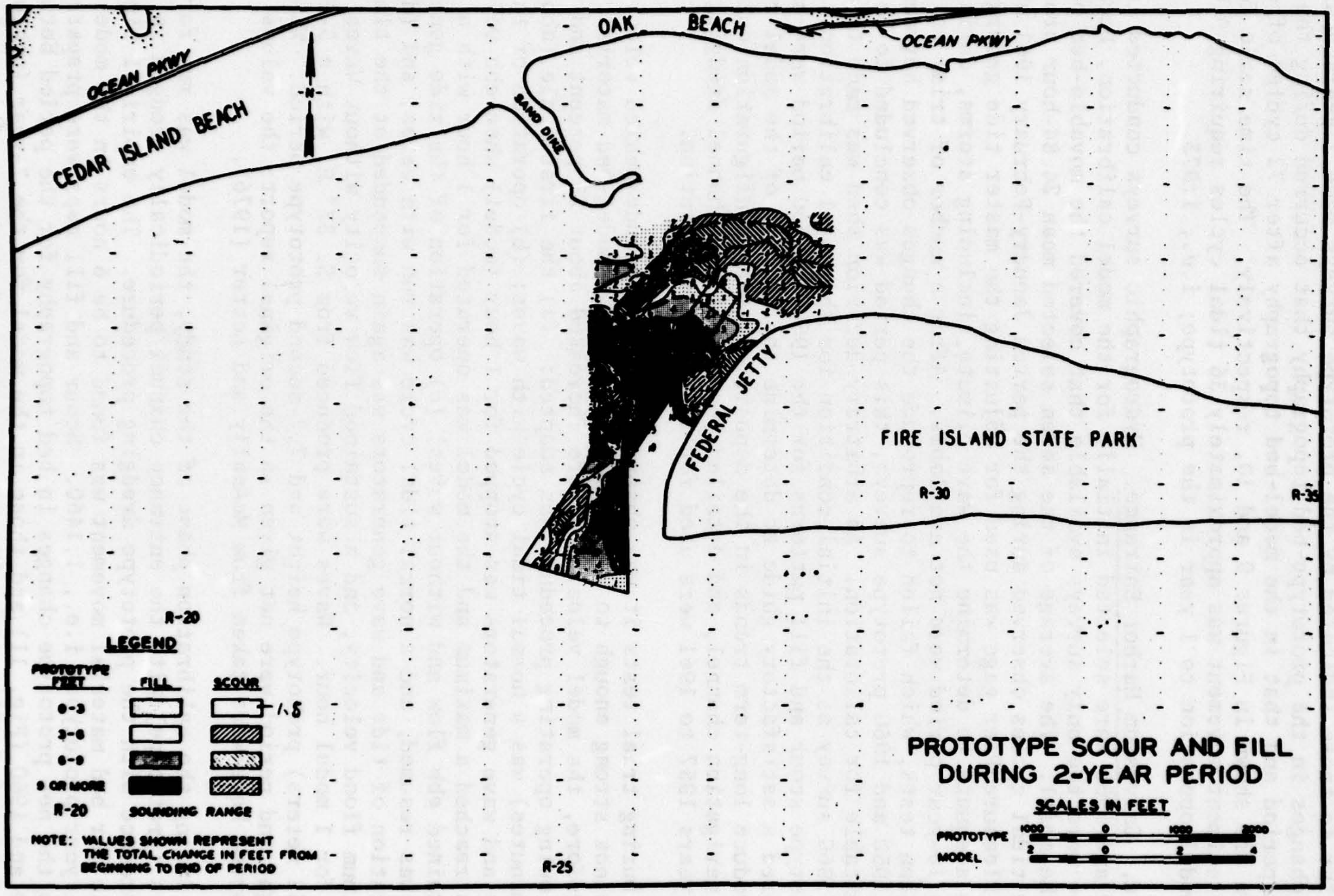

Figure 9. Prototype scour and fill in the Fire Island Inlet.

each, it was found that the changes in the model-bed topography were very similar to those indicated by the prototype surveys made 2 years apart. The changes in the prototype-bed topography that occurred during the 2-year period and that in the model-bed topography after 72 cycles of operation are shown in Figures 9 and 10, respectively. The time scale for the sediment movement was approximately 36 tidal cycles requiring 9 hours of model operation to 1 year in the prototype; i.e., 1:973.

d. Galveston Harbor Entrance. Hydrographic surveys conducted in 1950 and 1960 were selected initially for the model calibration, because these were the only surveys available that covered the movable-bed part of the model. The average of the seven selected mean 24.84-hour prototype tidal cycles observed during the period January-February 1961 at the Pleasure Pier gage was used for adjusting the master tide generator. Data adequate to determine the wave climate, including storms, during this 10-year period were not available. After a number of trial calibration tests, which failed to reproduce the changes observed between the 1950 and 1960 prototype surveys, this period was concluded to be unsuitable for calibration. An arbitrary decision then was made to use the 1960 survey as the initial condition for the model calibration. Prototype scour and fill patterns for the 1950 to 1960 period were considered a satisfactory guide to determine the ability of the model to reproduce long-term trends in the deposition-scour configuration outside the navigation channel, and detailed records of the channel dredging for the years 1957 to 1961 were used for the model calibration.

During trial tests it was observed that the Froude-scaled velocities were not strong enough to affect movement of the model-bed material. Therefore, the model velocities were increased about 35 percent and the following operating procedure was adopted: (a) the first cycle (about 30 minutes) was a normal tidal cycle with waves; (b) operation of the tide and wave generators was stopped for 1 hour (model) when ebb velocities reached a maximum and the model was operated for 1 hour with a sustained ebb flow and without waves; (c) operation of the tide generator was resumed, and a normal tidal cycle was run with waves; and (d) operation of tide and wave generators was again suspended at the time of maximum flood velocity, and a sustained flow velocity without waves was run for 1 model hour. Waves were produced from S. 37° E. with a 5-foot (1.52 meters) prototype height and 7.7-second prototype period. Wave height and period were not given in the original report; the values reported here were taken from McAnally and Letter (1976).

During the calibration phase of the study, the model was run for 7 years (prototype) with the entrance channel periodically dredged in accordance with the prototype dredging procedure. The empirical time scale for bed material movement was found to be 6 hours in the model to 1 year prototype; i.e., 1:1460. Scour and fill maps were prepared to show the net prototype changes in bed topography for the period between 1950 and 1960 (Fig. 11) and those in the model for the 7-year (prototype) running period (Fig. 12). Visual comparison of these two figures led the investigators to conclude that the model reproduced, with good accuracy,

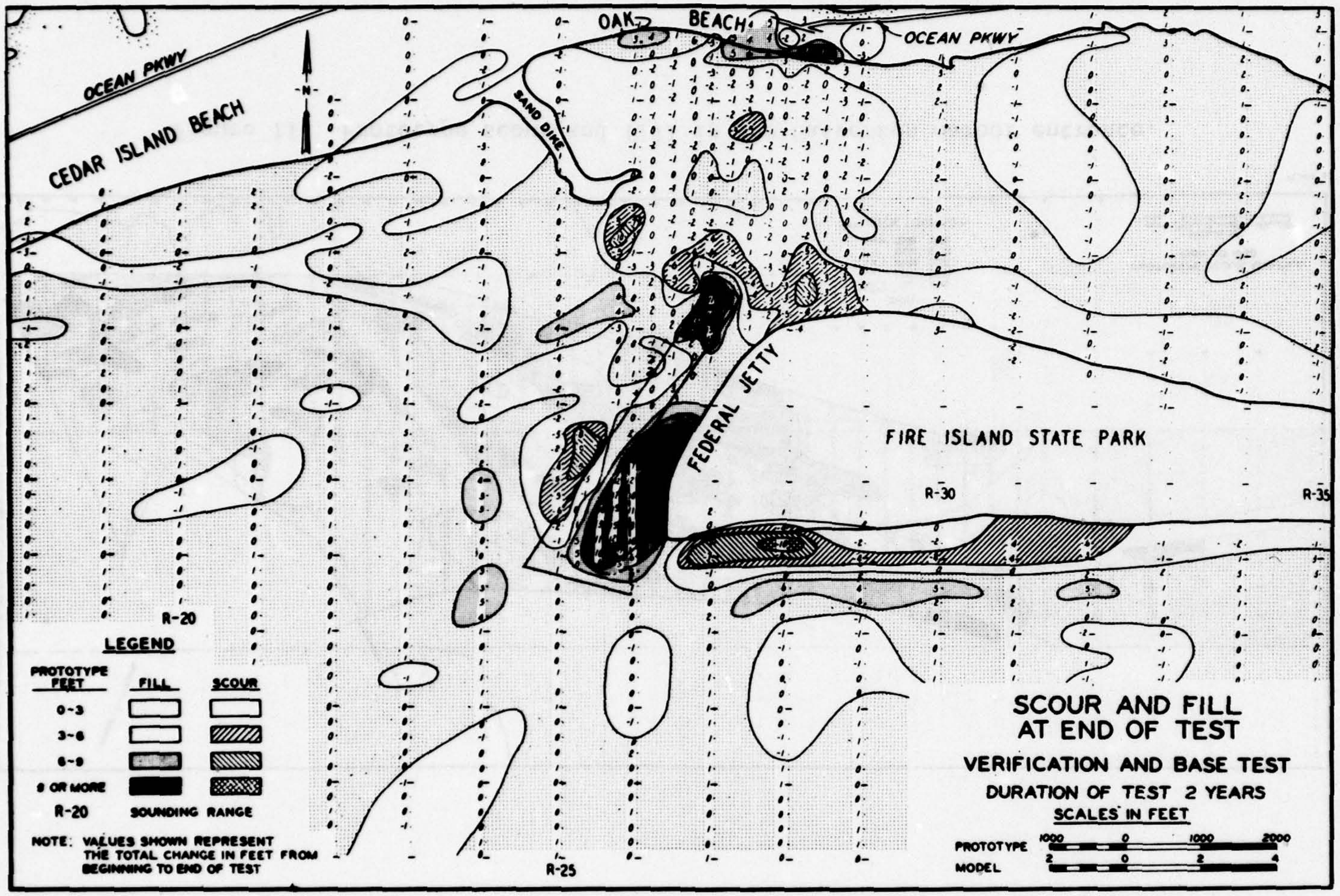

Figure 10. Model scour and fill in the Fire Island Inlet.

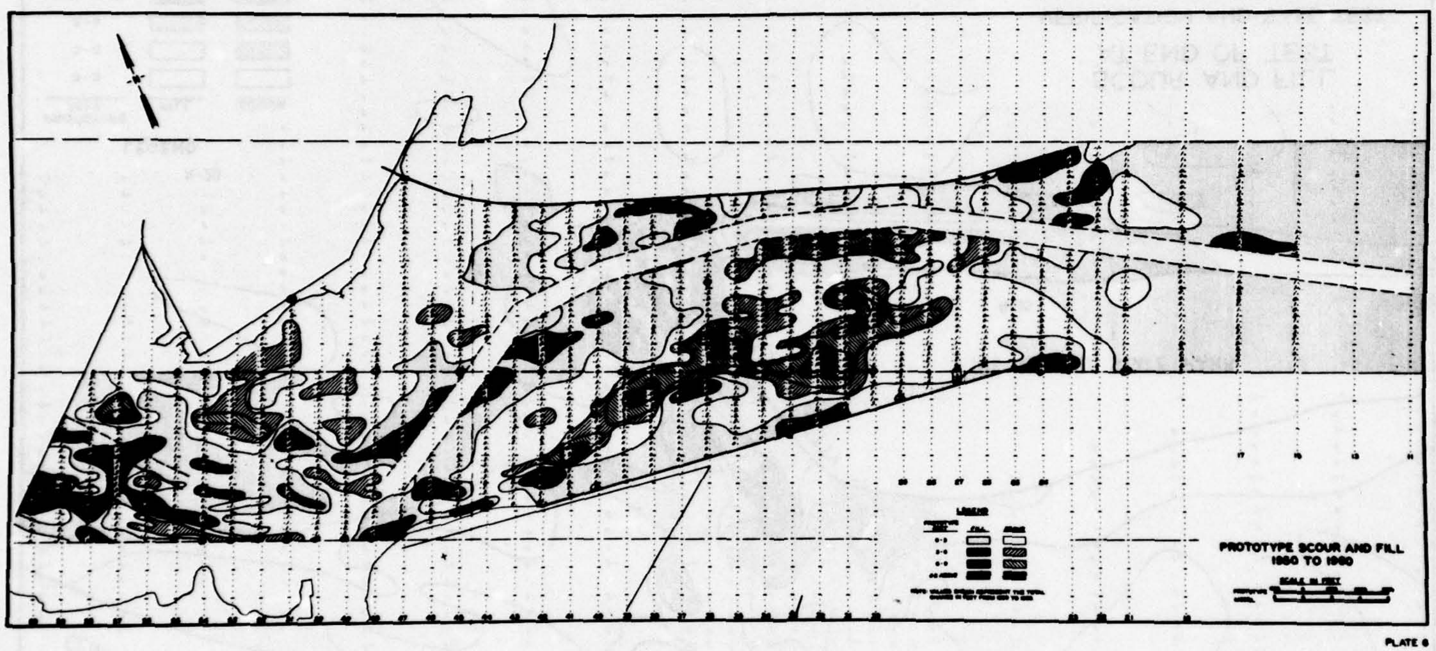

Figure 11. Prototype scour and fill in the Galveston Harbor entrance.

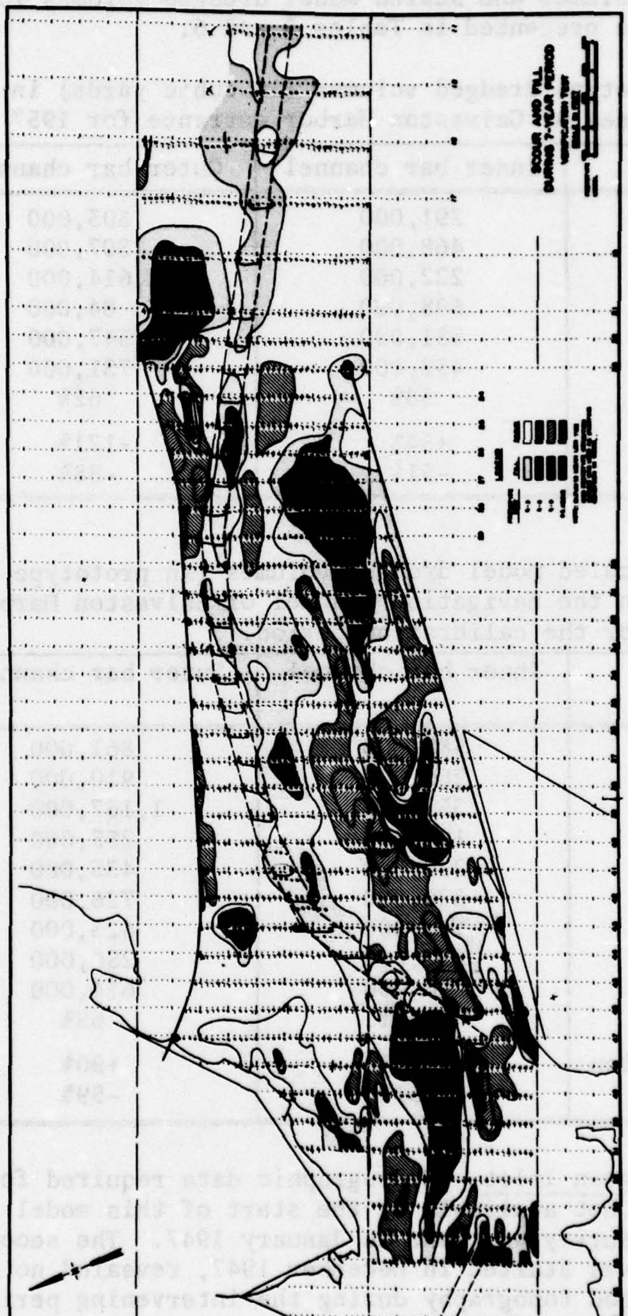

Figure 12. Model scour and fill in the Galveston Harbor entrance.

at least the trends of topographic changes in the prototype. The prototype dredged volumes and scaled model dredged volumes for the calibration period are presented in Tables 5 and 6.

Table 5. Prototype dredged volumes (in cubic yards) in the navigation channel of Galveston Harbor entrance for 1957 to 1961.

Fiscal year	Inner bar channel	Outer bar channel	Total
1957	291,000	303,000	594,000
1958	468,000	307,000	775,000
1959	222,000	1,614,000	1,836,000
1960	698,000	84,000	782,000
1961	581,000	1,347,000	1,928,000
Average	452,000	731,000	1,183,000
Distribution	38%	62%	100%
Maximum	+54%	+121%	+55%
Variations	-51%	-88%	-50%

Table 6. Scaled model dredged volumes (in prototype cubic yards) in the navigation channel of Galveston Harbor entrance for the calibration period.

Period (yr)	Inner bar channel	Outer bar channel	Total
1	588,000	861,000	1,449,000
2	266,000	910,000	1,176,000
3	352,000	1,167,000	1,520,000
4	190,000	255,000	445,000
5	232,000	435,000	667,000
5-yr avg	326,000	726,000	1,057,000
6	140,000	423,000	563,000
7	237,000	250,000	437,000
7-yr avg	286,000	614,000	901,000
Distribution	32%	68%	100%
Maximum variation	+106%	+90%	+69%
from 7-yr avg	-51%	-59%	-51%

e. Lynnhaven Inlet. Hydrographic data required for calibration of the model were not available at the start of this model study. The first comprehensive survey was made in January 1947. The second hydrographic survey, which was started in December 1947, revealed no significant change in the bed topography during the intervening period. The analysis of earlier hydrographic surveys of the area (before 1947) indicated that the bathymetry throughout the area had reached a state of stability. The predominant movement of sand was from east to west. The model was then adjusted to produce continuous movement of material in this direction over the entire movable-bed section, and at the same time maintain a fairly stable bed topography. Prototype tide data were available for 10

stations and velocity data for 4 stations in the area covered by the model (Fig. 13). The tidal range at the entrance to the inlet was approximately 3 feet for a spring tide. No prototype wave data are given in the report. Tides and current velocities reproduced in the model were in accordance with the prototype data.

By means of trial and error, 5-foot-high, 160-foot-long (48.77 meters) (prototype) waves were selected for reproduction in the model. The calibration test was started with the movable-bed section contoured to model the January 1947 prototype survey, and was continued through 12 complete cycles of tides, waves, and littoral currents (about 3.5 hours model). The changes in the bed configurations which occurred during the course of the tests are presented in Figure 13, which shows that the overall condition of the movable bed did not change appreciably during the test. The rate of littoral drift in the model was considerably greater than that estimated to occur in the prototype.

f. Masonboro Inlet. As discussed previously, the movable-bed model study of Masonboro Inlet was undertaken under the GITI research program to determine the usefulness and reliability of then current physical and numerical modeling techniques in predicting prototype behavior. This inlet was chosen for the GITI program study because prototype survey data were available on the preconstruction condition of the inlet area, and hydrographic surveys had been performed at approximately 6-month intervals subsequent to construction of the north jetty. In addition, there was some interest in the inlet itself and thus fixed-bed model studies had been run. No information on the prototype wave and tide data is given in the report on this study.

Only two of the prototype hydrographic surveys obtained before construction of the jetty (October 1964 and August 1965, a 9-month interval), were usable and were selected for model calibration. Thirty-nine model tests were made in an attempt to reproduce the changes in the bed configuration that occurred in the prototype during the 9-month period. Model wave heights, periods, directions, sequences, and distributions were adjusted during the calibration tests. Tidal heights, mean tide levels, test durations, beach feeding rates and techniques, and bay surface area were also varied. No single model test produced results over the entire problem area which could be judged to have calibrated the model. Some tests produced fair results seaward of the shoreline and poor results bayward of the beach; others produced results that were in fair agreement with prototype data bayward but not seaward of the shoreline.

Tests 19 and 38 resulted in the best reproduction of the bed topography seaward of the shoreline and bayward of the shoreline, respectively. The model test conditions for these two tests are given in Table 7. The scour-fill map for the prototype for the period October 1964 to August 1965 is shown in Figure 14. Figures 15 and 16 show the scour and fill patterns which develop in tests 19 and 38, respectively.

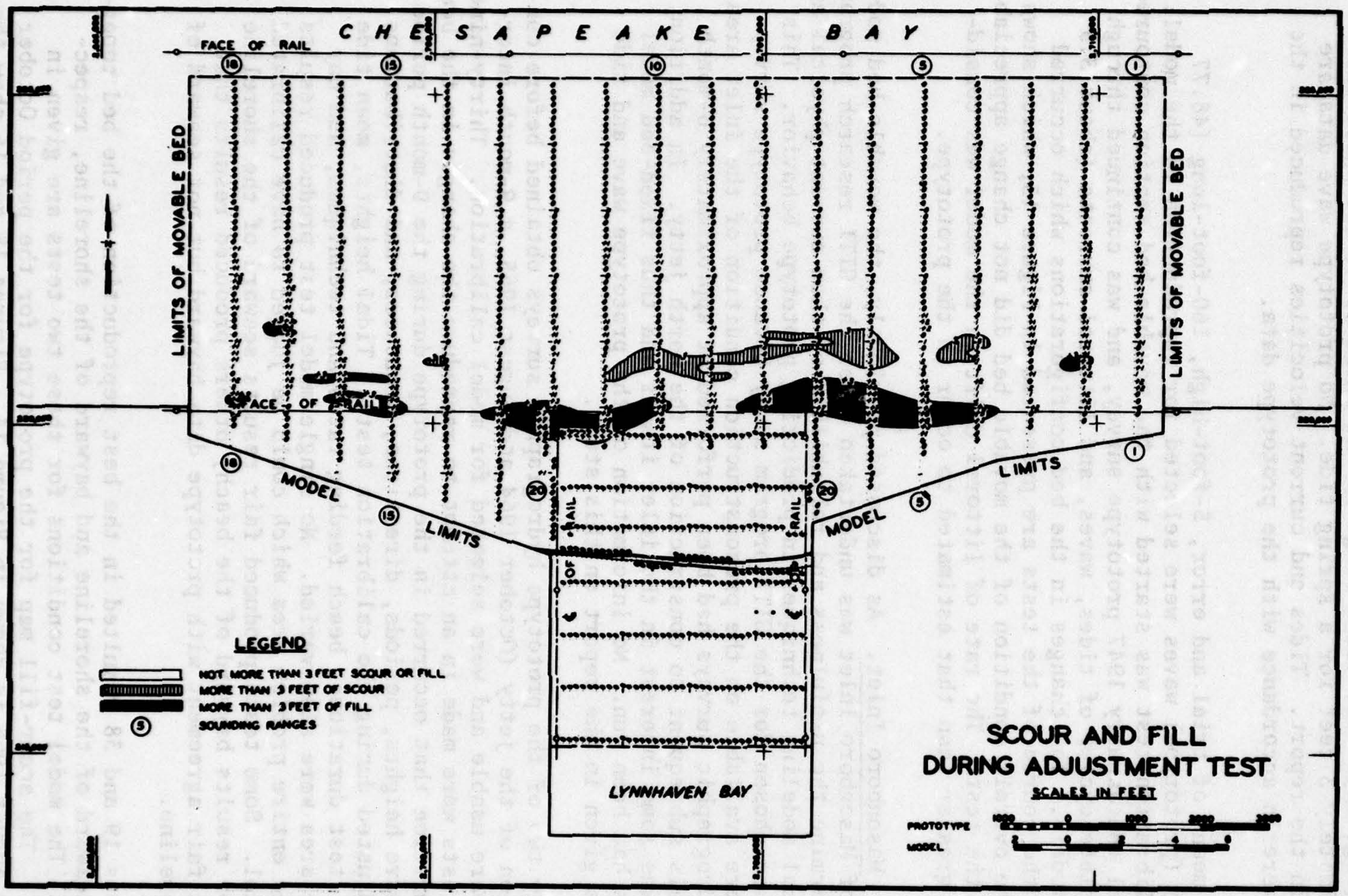

Figure 13. Model scour and fill in the Lynnhaven Inlet.

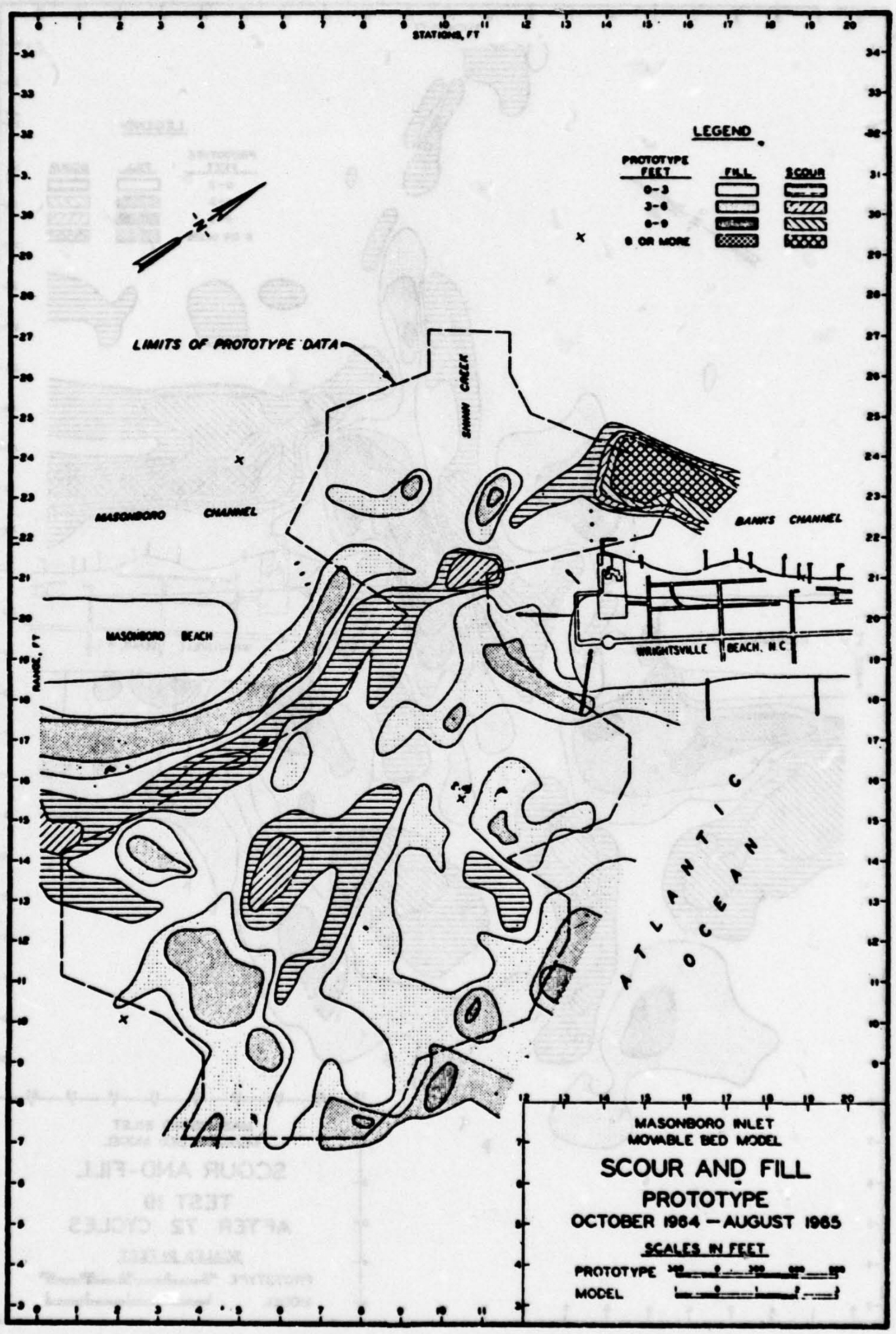

Figure 14. Prototype scour and fill in the Masonboro Inlet.

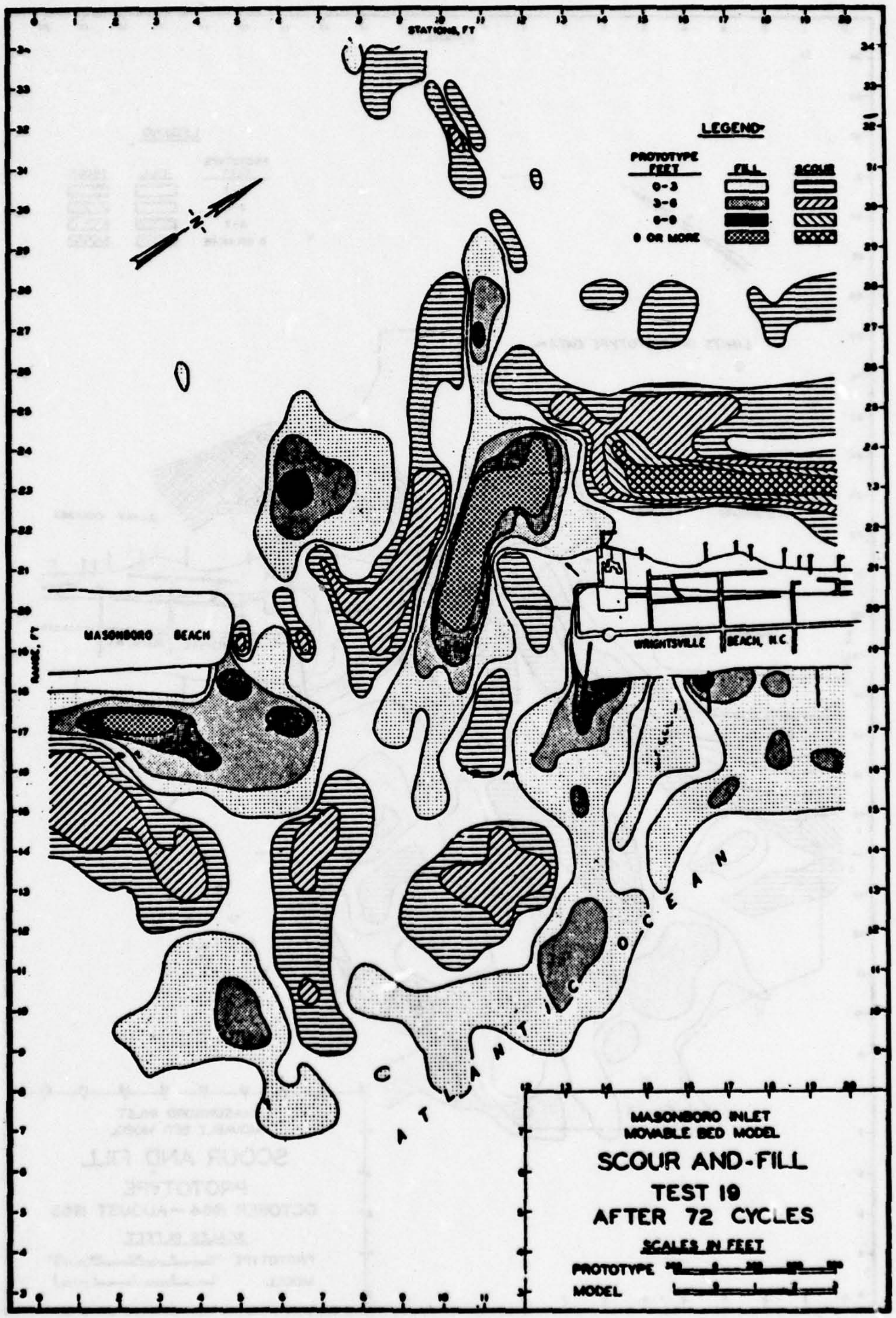

Figure 15. Model scour and fill in the Masonboro Inlet (test 19).

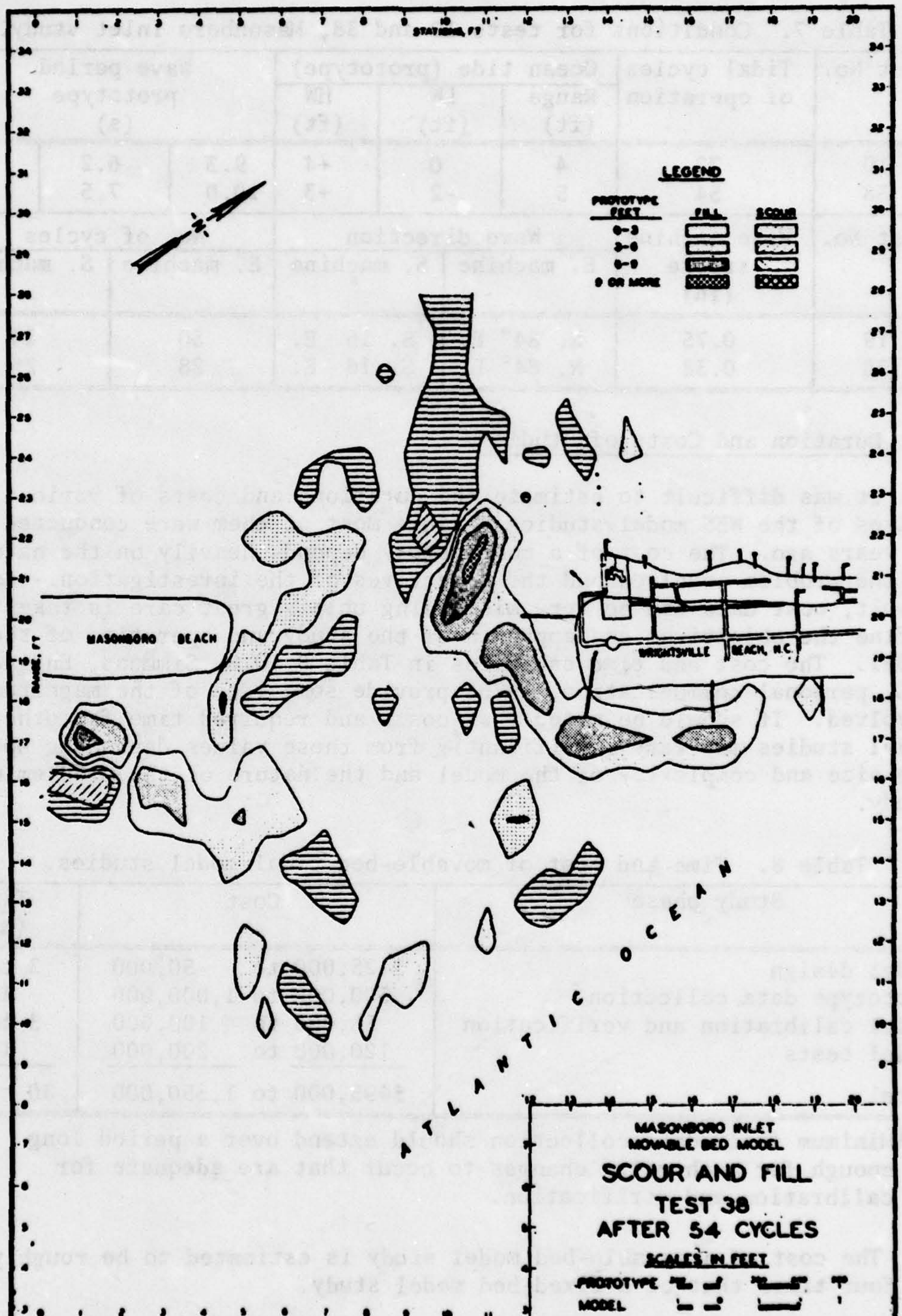

Figure 16. Model scour and fill in the Masonboro Inlet (test 38)

Table 7. Conditions for tests 19 and 38, Masonboro Inlet study.

Test No.	Tidal cycles of operation	Ocean tide (prototype) Range (ft)	LW (ft)	HW (ft)	Wave period prototype (s)		
19	72	4	0	+4	9.3	6.2	4.6
38	54	5	-2	+3	10.0	7.5	5.0

Test No.	Wave machine stroke (in)	Wave direction E. machine	Wave direction S. machine	No. of cycles E. machine	No. of cycles S. machine
19	0.75	N. 84° E.	S. 16 E.	30	24
38	0.38	N. 84° E.	S. 16 E.	28	26

7. Duration and Costs of Studies.

It was difficult to estimate the durations and costs of various phases of the WES model studies because most of them were conducted 5 to 30 years ago. The cost of a model study depends heavily on the nature of the problem involved and the objectives of the investigation. As a result, cost data can be very misleading unless great care is taken to define the objectives and approach of the study and operation of the model. The cost and time estimates in Table 8 (H.B. Simmons, Engineer, WES, personal communication, 1976) provide some idea of the magnitudes involved. It should be noted that costs and required time for other model studies may vary significantly from these values depending upon the size and complexity of the model and the nature of the problem under study.

Table 8. Time and cost of movable-bed tidal model studies.

Study phase	Cost	Time (mo)
Model design	$ 25,000 to 50,000	3 to 6
Prototype data collection	300,000 to 1,000,000	12[1]
Model calibration and verification	50,000 to 100,000	3 to 9
Model tests	120,000 to 200,000	12
Total	$495,000 to 1,350,000	30 to 39

[1]Minimum field data collection should extend over a period long enough for bathymetry changes to occur that are adequate for calibration and verification.

The cost of a movable-bed model study is estimated to be roughly two to four times that of a fixed-bed model study.

Here it must be emphasized that collection of prototype data is one of the most important phases of any movable-bed tidal model study. The levels of understanding and mathematical formulation of sediment transport by unsteady flows are such that extensive model calibration and

verification are essential to the satisfactory conduct of a model study. Accordingly, prototype data on waves, currents, and sedimentary changes covering at least a 1-year period, and preferably including one or more storm events, are essential to calibration of the model. Additionally, data on the sedimentary response of the study area to a structure of other induced change are desirable for model verification. The descriptions of the WES model studies indicate that they generally were deficient in prototype data for calibration, in most instances to the point that it is questionable whether the model study should have been initiated until adequate prototype data were made available. Verification data were not available for the WES studies.

IV. ANALYSIS OF MODEL VERIFICATION AND AN EVALUATION OF WES RESULTS

1. General.

None of the movable-bed tidal inlet hydraulic model studies conducted by WES had more than two sets of prototype bathymetric data available at the time of the investigation. As a result, those models which could be calibrated could not be verified. The WES procedure for determining whether a model had been calibrated satisfactorily was to prepare a scour-fill map from the model results and compare the pattern of bed bathymetry change with that measured in the prototype during the corresponding time period. Examples of these scour-fill maps are shown in Figures 5 to 16. If the general pattern of scour and fill was similar in model and prototype, the model was judged to have been calibrated satisfactorily. In some studies comparisons of the dredging volumes were also used in the model calibration. This "visual" comparison of the scour and fill patterns to determine the adequacy of the calibration involves a strong element of subjectivity. Therefore, quantitative measures of the adequacy of calibration and verification should be developed. A discussion of the quantitative indicators developed and used in this study follows.

2. Quantitative Indicators.

The measures of accuracy of calibration described below are based on quantitative comparisons of profiles measured along corresponding cross sections or ranges in model and prototype. Let the initial and final (before and after a calibration test) bed profiles along the jth range be as shown in Figure 17. Further, let D_{ij} be the change in the bottom elevation at point (i,j) (i.e., at the ith point on the jth range) during the time interval between the two hydrographic surveys used for model calibration. Ideally, the values of D_{ij} in the model and prototype should be the same. The degree to which changes in elevation at corresponding points in the model are related to those in the prototype can be measured by the correlation coefficient defined for the area of concern by

$$R_D = \frac{1}{\left(\sum_{j=1}^{N} M_j\right) - 1} \sum_{i=1}^{N} \sum_{i=1}^{M_j} \frac{(D_{ij} - \overline{D}_{ij})_m (D_{ij} - \overline{D}_{ij})_p}{\sigma_{D_m} \sigma_{D_p}} \qquad (20)$$

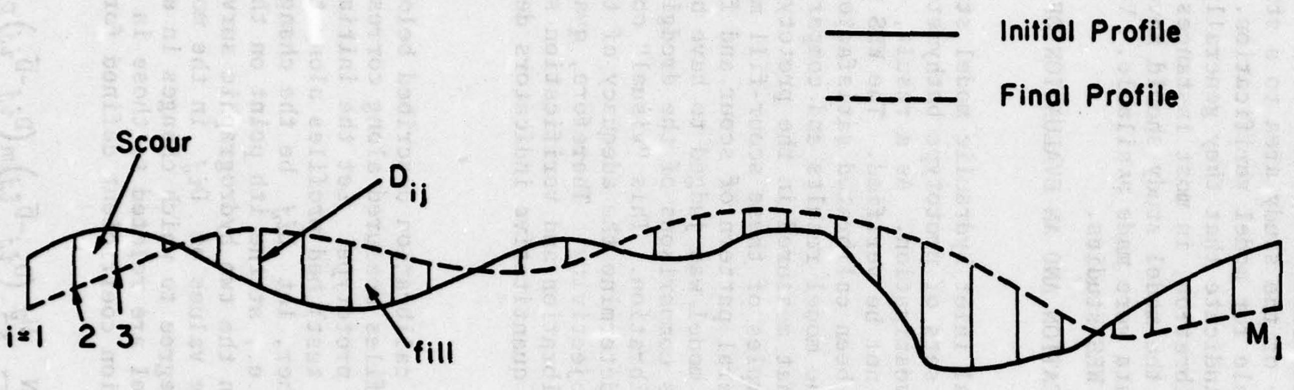

Figure 17. Initial and final bed profiles at jth cross section.

where N is the number of cross sections, M_j is the number of data points in the jth cross section, the overbar denotes the average value, σ is the standard deviation of the quantity symbolized by the subscript, and the suffixes m and p denote model and prototype, respectively. A value of R_D of unity corresponds to perfect correlation, zero signifies no correlation, and a negative value indicates a reverse correlation (i.e., a high probability of occurrence of scour (fill) at a point in the model where there is fill (scour) in the prototype). Given the present state of the modeling art, it is unrealistic to expect a high value of R_D from a model.

In addition to computing the correlation between the changes in the bottom elevations on a point-to-point basis (i.e., computing R_D), the correlation between the average model and prototype depth changes over each of the cross sections can be determined. Let S_j and F_j be the total amount of scour or fill, respectively, per unit width over the jth profile during a given time interval (see Fig. 17). Define $Q_j' = (S_j - F_j)$; thus, Q_j' is a measure of the average depth change over the jth profile. It is also a measure of the net sediment transport into or out of the area immediately surrounding the jth profile in the given time interval. If the points along the jth section where the bed elevations are measured are equally spaced at interval ℓ then

$$Q_j' = \ell \sum_{i=1}^{M_j} D_{ij} \tag{21}$$

The degree to which the average model depth change over the jth profile is related to that in the prototype is expressed by the correlation coefficient

$$R_Q' = \frac{1}{N-1} \sum_{j=1}^{N} \frac{\left(Q_{jm}' - \overline{Q_{jm}'}\right)\left(Q_{jp}' - \overline{Q_{jp}'}\right)}{\sigma_{Q_m'} \; \sigma_{Q_p'}} \; . \tag{22}$$

A large value of R_Q' indicates a high degree of correlation between model and prototype of $(S_j - F_j)$ for that profile. Strong correlations of both $(S_j - F_j)$ and $(S_j + F_j)$ assures high model-prototype correlations between S_j and F_j separately. However, some individual points along a profile might have quite dissimilar changes in model and prototype. Let $Q_j = (S_j + F_j)$; then

$$Q_j = \ell \sum_{i=1}^{M_j} \left| D_{ij} \right| \tag{23}$$

and its correlation coefficient is given by

$$R_Q = \frac{1}{N-1} \sum_{j=1}^{N} \frac{\left(Q_{jm} - \overline{Q}_{jm}\right)\left(Q_{jp} - \overline{Q}_{jp}\right)}{\sigma_{Q_m} \sigma_{Q_p}} . \tag{24}$$

The way in which Q_j and Q'_j are defined eliminates the necessity of determining S_j and F_j, which are relatively difficult to compute. However, the quantities Q_j and Q'_j can be computed easily from the raw data. A reasonable calibration or verification of the model requires high values of both R_Q and R'_Q.

Another simple statistical quantity which can be used to evaluate the degree of conformity between model and prototype is the root-mean-square (rms) error, E, which is given by

$$E \equiv \sqrt{\overline{\Delta D_{ij}^{\,2}}} \equiv \sqrt{\frac{1}{\sum_{j=1}^{N} M_j} \sum_{j=1}^{N} \sum_{i=1}^{M_j} \left(\Delta D_{ij}\right)^2} \tag{25}$$

in which

$$\Delta D_{ij} = \left(D_{ij}\right)_p - \left(D_{ij}\right)_m . \tag{26}$$

These statistical measures of model-prototype agreement must be interpreted carefully to avoid misunderstanding. Linear correlation coefficients can show a low degree of correlation even when a strong nonlinear correlation exists; e.g., if the model produced scour and fill in the proper locations but underpredicted the magnitude of change by an amount dependent on depth change. However, nonlinear behavior of this type would be considered a deficiency of the model. Net change in cross-sectional area, given by Q'_j, tends to be small in stable inlets, so its value may be too small, in relation to sounding error, to be of significance in correlation computations. Statistical measures of agreement can also be biased by a lack of similarity in areas that are not of interest in the study; therefore, the quantitative measures of agreement should be calculated only for the areas that are of importance in the study.

3. Results.

To obtain quantitative estimates of the degree of model calibration achieved, values of the correlation coefficients defined in equations (20), (22), and (24) and the rms error given by equation (25) were computed for five of the model studies conducted by WES. Values were not computed for Lynnhaven Inlet model because no prototype data were available. It is possible to obtain low values of the correlation coefficients in situations in which the value of D_{ij} at several points, both in model and prototype, is small but the ratio $(D_{ij})_m/(D_{ij})_p$ is either

negative or varies widely. These small differences in D_{ij} between model and prototype can occur due to errors in measuring bed topography in model and prototype. To allow for this possibility the values of $(D_{ij})_m$ were modified in the following way and the correlation coefficients and the rms errors were computed for the modified values. For a point at which $|\Delta D_{ij}| < K$ the modified value of $(D_{ij})_m$ was taken to be equal to $(D_{ij})_p$; if $\Delta \overline{D}_{ij} > K$, the modified value of $(D_{ij})_m$ at that point was taken equal to $(D_{ij})_m + K$. Finally, if $\Delta D_{ij} < - K$, the modified value of $(D_{ij})_m$ was set equal to $(D_{ij})_m - K$. The computations were made for K = 0, 1, 2, and 3 (units of K same as for D_{ij}).

Table 9 gives the background data for the calculation of the statistical quantities for five of the WES studies. The values of the correlation coefficients and of the *rms* errors for these studies are given in Table 10.

Table 9. Background for computing quantitative indicators for the WES studies.

Inlet model study	Data points (No.)	Cross sections (No.)	Source of data points
Absecon	1,516	50	Figs. 5 and 6
Barnegat	547	21	Figs. 7 and 8
Fire Island	136	15	Figs. 9 and 10
Galveston	1,437	38	Figs. 11 and 12
Masonboro, test 19	162	21	Figs. 13 and 14
Masonboro, test 38	144	18	Figs. 15 and 16

4. Discussion of Results.

In general, the values of the correlation coefficients, R_Q' and R_D, are low and the rms errors are high for K = 0. For K values of 2 or 3 feet, which correspond to the expected combined data accuracies given in Section III, the results are mixed. For Absecon Inlet R_Q was high, R_Q' was low, and the rms error was about 2 feet. Barnegat showed a strong correlation of both R_Q and R_Q' but still exhibited an rms error of about 2 feet. Fire Island results were curious in that the correlation coefficients were fairly high but the error was about 4 feet. Correlations for Galveston were substantially lower than the others; the rms error was about 4 feet, and equal to that of Fire Island. Masonboro Inlet demonstrated higher correlation and lower rms error for the outer region than the inner region except for R_Q. The correlation coefficients R_Q' and R_D for some model studies, e.g., Absecon Inlet and Galveston Harbor entrance, are negative, which indicates that the model predicted scour at some locations where deposition occurred in the prototype, and vice versa. The values of R_D and R_Q' for the Absecon Inlet model are strongly negative for the smaller values of K. To investigate whether the model performance was unsatisfactory over only a part or the entire area of the model, the modeled area was arbitrarily divided into five subregions and the correlation coefficients were computed for each, with the results presented in Table 11. The values of R_D and

Table 10. Values of correlation coefficients (in feet) and rms errors (in feet) for the WES studies.

	K = 0	K = 1 ft	K = 2 ft	K = 3 ft
Absecon Inlet				
R_Q	0.83	0.84	0.89	0.91
R'_Q	-0.82	-0.71	-0.27	0.58
R_D	-0.48	-0.27	0.09	0.47
E	3.65	2.93	2.32	1.81
Barnegat Inlet				
R_Q	0.64	0.74	0.85	0.93
R'_Q	0.44	0.60	0.75	0.85
R_D	0.22	0.52	0.74	0.87
E	3.51	2.80	2.20	1.68
Fire Island Inlet				
R_Q	0.49	0.56	0.66	0.78
R'_Q	0.66	0.75	0.83	0.90
R_D	0.51	0.64	0.74	0.82
E	6.07	5.29	4.57	3.92
Galveston Harbor Entrance				
R_Q	0.08	0.15	0.27	0.43
R'_Q	-0.09	0.13	0.37	0.55
R_D	-0.12	0.01	0.17	0.33
E	5.33	4.65	4.05	3.53
Masonboro Inlet, Test 19 (Inner Region)				
R_Q	0.76	0.80	0.84	0.90
R'_Q	-0.60	-0.46	-0.16	0.29
R_D	0.36	0.45	0.56	0.66
E	4.46	3.78	3.15	2.59
(Outer Region)				
R_Q	0.43	0.57	0.74	0.90
R'_Q	0.56	0.68	0.80	0.89
R_D	0.39	0.56	0.72	0.84
E	2.72	2.06	1.53	1.10
Masonboro Inlet, Test 38 (Inner Region)				
R_Q	0.23	0.54	0.76	0.90
R'_Q	0.46	0.37	0.34	0.44
R_D	-0.03	0.19	0.41	0.61
E	3.36	2.75	2.30	1.90
(Outer Region)				
R_Q	0.34	0.58	0.74	0.87
R'_Q	0.42	0.78	0.92	0.98
R_D	0.28	0.69	0.87	0.96
E	1.99	1.36	0.91	0.55

Table 11. Values of the correlations coefficients for five subregions of Absecon Inlet.

	K = 0	K = 1 ft	K = 2 ft	K = 3 ft
		Region 1		
R_Q	0.97	0.99	0.99	0.99
R'_Q	-0.89	-0.86	-0.76	-0.03
R_D	-0.65	-0.52	-0.20	0.25
		Region 2		
R_Q	0.92	0.91	0.86	0.79
R'_Q	-0.82	-0.74	-0.54	0.08
R_D	-0.39	-0.25	-0.02	0.30
		Region 3		
R_Q	0.89	0.89	0.94	0.95
R'_Q	-0.61	-0.45	-0.08	0.50
R_D	-0.41	-0.13	0.25	0.56
		Region 4		
R_Q	0.92	0.96	0.94	0.91
R'_Q	-0.92	-0.90	-0.30	0.85
R_D	-0.67	-0.55	-0.28	0.13
		Region 5		
R_Q	0.92	0.91	0.93	0.95
R'_Q	-0.82	-0.59	0.08	0.72
R_D	-0.21	-0.01	0.31	0.64

R'_Q for each subregion also are strongly negative for the smaller K values, which show that the bed topography changes in the model were a poor representation of those in the prototype over practically all parts of the area reproduced in the model. At the suggestion of CERC (R. Sorenson, personal communication, 1976) the values of the differences between prototype- and model-bed elevation changes, ΔD_{ij}, for the Absecon Inlet model were plotted and 3-foot interval contours were drawn. The results are shown in Figure 18. Over a large part of the modeled area the differences between prototype- and model-bed elevation changes were more than 3 feet. This graphical method of checking the agreement between model and prototype changes in the bed topography appears to be less subjective than that in which the scour and fill maps for model and prototype are compared.

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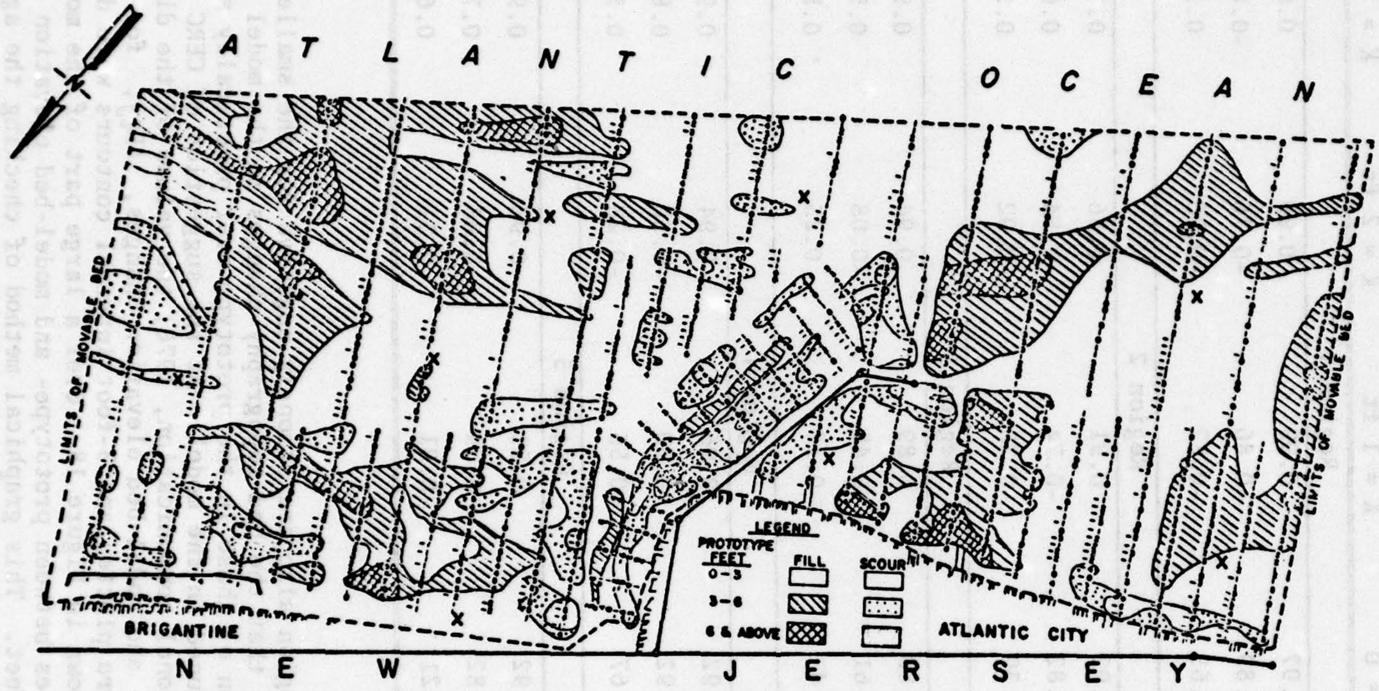

Figure 18. Values of the differences between prototype- and model-bed elevation changes for the Absecon Inlet model.

A comparison of the values of the correlation coefficients for the various models shows that the calibrations of the Barnegat Inlet and the Fire Island Inlet models were generally superior to the calibrations of the others. This may have been due to several factors. In these two models, no dredging was required, while in the others bed material was removed from the channels periodically to reproduce prototype dredging. Because the sedimentary time scale was not known at the time of the calibration tests, it was impossible to dredge the model channel at proper times. Furthermore, better prototype data were available for calibration of these two models. The calibration periods covered 2 and 3 years, which is a reasonably long timespan. Some prototype wave data were also available. Finally, waves of different heights, periods, and from two different directions were reproduced in these two models.

Only in the Galveston Harbor entrance and the Absecon Inlet model studies were efforts made to model removal of the maintenance dredging volumes from the navigation channel during the calibration tests. For the Galveston Harbor entrance model, the calibration of the model was based primarily on the volumes of sediment dredged from the channel (see Tables 5 and 6). The dredged volumes, both in the model and the prototype, varied from year to year. In the prototype these variations were due to changes in the current and wave environments, as well as to other factors such as availability of dredging equipment, channel maintenance funding levels, and use of advance maintenance and overdepth dredging procedures. However, the exact reasons for variations in the model volumes is unclear. Although the average dredged volumes for the 5 years in the model are in fair agreement with that of the prototype, there appears to be no justification to base the calibration of the model on these averaged values. The moving averages of the dredged volumes for both model and prototype are given in Table 12. The running averages in the model and prototype have opposing trends; the volume decreases with time in the model, but increases in the prototype. Therefore, at some time the two values had to be in fair agreement.

For the Absecon Inlet model, although the dredged volume in the model navigation channel for the 3-year calibration period was reported to be within 8 percent of that in the prototype, the temporal staging of removal of the dredged volume from the model was not reported. Therefore the moving averages of the dredged volumes for model and prototype could not be compared.

Table 12. Running average of the dredged volume in the navigation channel of the Galveston Harbor entrance.

Avg	Model (1,000 yd^3)			Prototype (1,000 yd^3)		
	Inner bar channel	Outer bar channel	Total	Inner bar channel	Outer bar channel	Total
1 yr	588	861	1,449	291	303	594
2 yr	427	885	1,312	379	305	684
3 yr	402	979	1,381	327	741	1,068
4 yr	349	798	1,147	419	577	996
5 yr	325	725	1,050	452	731	1,183

For the Masonboro Inlet study, WES recognized that the 9-month interval between the two prototype hydrographic surveys, which were used for the model calibration, was not long enough to provide adequate data for the calibration.

V. AN EVALUATION OF GALVESTON HARBOR ENTRANCE MOVABLE-BED MODEL

1. General.

The Galveston Harbor entrance was the only tidal inlet included in this investigation for which the modification plan modeled was constructed in the prototype, and reasonably complete prototype data for the postconstruction period were obtained. In this section, the model-based predictions for the Galveston entrance model study are compared with the observations made in the prototype, and the effectiveness of this model in predicting later prototype occurrences is evaluated.

The Galveston Harbor entrance channel and its surroundings are shown in Figure 19. The north and south sides of the dredged channel are protected by jetties which extend about 5 and 7 miles, respectively, seaward into the Gulf of Mexico. The boundaries of the fixed-bed and movable-bed parts of the model, the original and realined entrance channels, and the locations of the master and secondary tide generators also are included in Figure 19. The original entrance channel was subject to continual rapid shoaling. The objective of the model study was to determine a channel alinement which would be navigationally superior to the original one and which would require less maintenance dredging. It should be noted that the new channel was to be 4 feet deeper than the original one.

The model scales adopted, the bed materials used, and the apparatus and procedure employed in the model study were described in Section III; the results of the model calibration were analyzed in Section IV. The model operating technique developed in the calibration phase of the study was followed in all subsequent tests. The tests followed a phased sequence of dredging, with the dredged material being disposed of in the offshore region and in the abandoned part of the original entrance channel. Construction of the realined modeled channel occupied 2 years (prototype); construction of the realined channel in the prototype required about 2.5 years and was completed in October 1967. The construction sequence and dredged spoil disposal techniques were similar to those followed in the model tests. Because construction times were slightly different in the model and prototype, the times used in comparing model and prototype predictions were measured from the time of completion of the modified channel.

2. Evaluation of Model Predictions.

The following prototype and model data on Galveston Harbor entrance for the postconstruction period (after completion of the realined channel) were provided by WES:

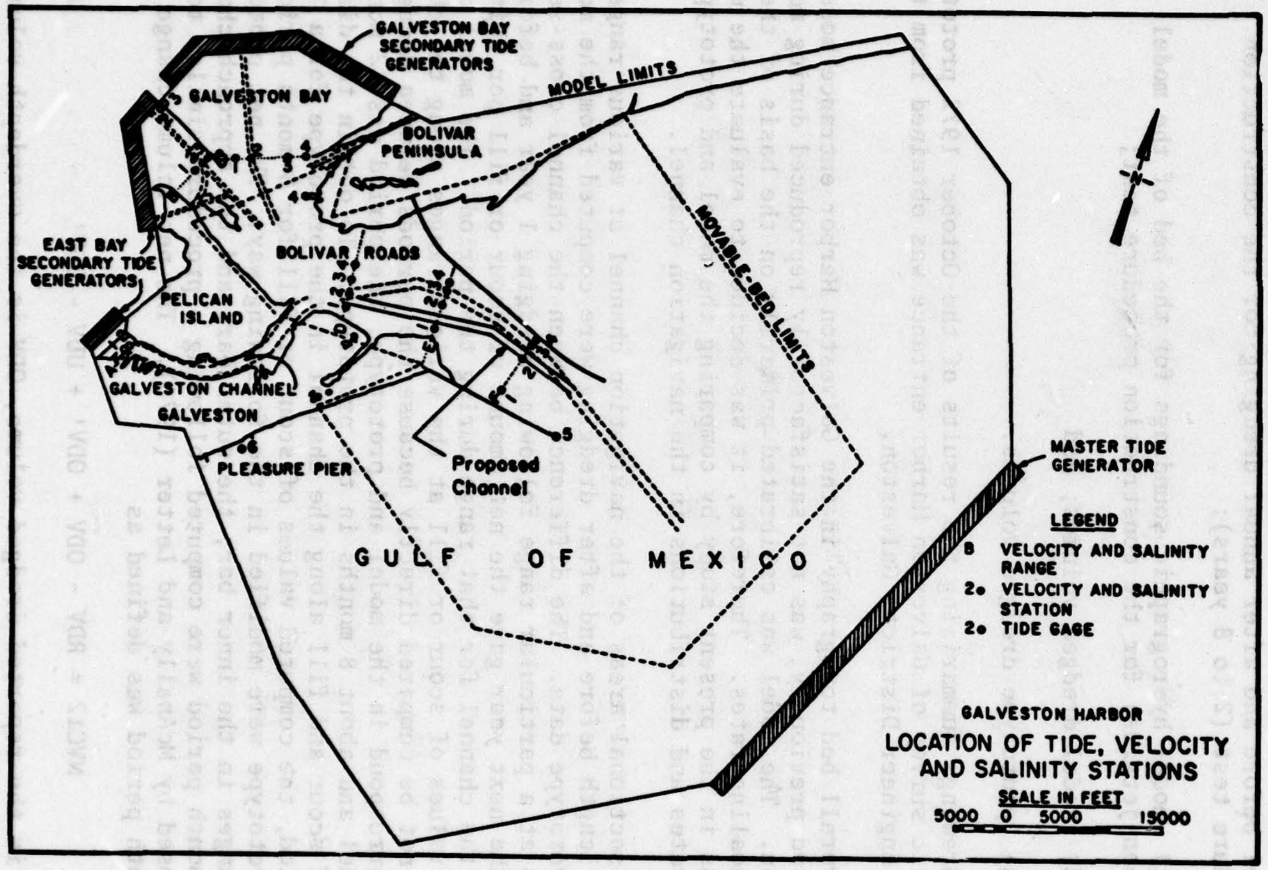

Figure 19. Schematic plan view of the Galveston Harbor entrance model.

(a) Prototype hydrographic soundings within the navigation channel just before and after dredging for 1969 to 1973;

(b) model hydrographic soundings within the navigation channel before and after annual dredging for the construction procedure test (2 to 8 years);

(c) model hydrographic soundings for the bed of the model (between jetties) for the construction procedure test;

(d) model dredged volumes; and

(e) prototype dredged volumes.

A set of drawings summarizing the results of the October 1972 prototype hydrographic survey of Galveston Harbor entrance was obtained from the U.S. Army Engineer District, Galveston.

The overall bed topography in the Galveston Harbor entrance model, as discussed previously, was not satisfactorily reproduced during model calibration. The model was calibrated primarily on the basis of the channel shoaling rates. Therefore, it was decided to evaluate the model predictions in the present study by comparing the model and prototype shoaling rates and distributions in the navigation channel.

Cross-sectional areas of the navigation channel at various ranges along its length before and after dredging were computed from the model and the prototype data. The difference between the channel cross-section areas at a particular range following dredging 1 year and before dredging the next year gave the net amount of scour or fill per unit length of the channel for that range during the period. The model and prototype values of scour or fill at the various ranges along the channel could not be compared directly because the periods between dredging did not correspond in the model and prototype; the period was 12 months in the model and about 8 months in the prototype. To obtain the distributions of scour and fill along the channel in the prototype for a 12-month period, the computed values of scour or fill for 8-month periods for the prototype were modified in the following way. The net prototype volume changes in the inner bar, the outer bar, and the approach channel for a 12-month period were computed following a procedure similar to that proposed by McAnally and Letter (1976). The net volume change for the 12-month period was defined as

$$NVC12 = RDV - ODV + ODV' + UDV - UDV' \qquad (27)$$

where RDV is the reported dredged volume, ODV is the overdepth volume for the year, ODV' is the overdepth volume for the previous year, UDV is the underdepth volume for the year, and UDV' is the underdepth volume for the previous year. Underdepth and overdepth volumes were determined from after-dredging surveys by calculating the areas above and below project depth for various channel cross sections along the channel and

obtaining volumes above or below project depth based on the length of channel associated with each cross section. The overdepth or underdepth volumes for the inner bar, the outer bar, and the approach channel were determined by totaling all the volumes above and below project depth for each section of the entrance channel. Let the net volume change in the prototype for the approximately 8-month-long period computed from the before-and-after dredging records be NVC8. The values of scour or fill at a particular cross section during the 12-month period were obtained by multiplying the scour or fill values for an 8-month period by the ratio NVC12/NVC8. It was assumed thereby that the rate of scour or fill for the following 4 months was the same as for the preceding 8 months.

The distributions of scour or fill along the channel for the third, fourth, and fifth year after the construction of the new channel, both for model and prototype, are shown in Figures 20, 21, and 22, respectively. The net volume changes along the inner bar, the outer bar, and the approach channel for both model and prototype are presented in Table 13. A comparison of the scour and fill volumes along the channel in the model and the prototype shows the model predictions to be in poor agreement with the prototype values. The maximum discrepancy occurs in the inner bar channel. The prototype net volume changes, NVC12, over most of the inner and outer bar channels for the fifth year after the construction of the channel based on equation (27) are negative (see Table 13). This would indicate that there was net scour in the channel during that particular year, which is unlikely. The computations of the volume changes, NVC8, in the inner and outer bar channels for the period following dredging the fourth year and before dredging the fifth year indicate fill in these channels. It appears, therefore, that the reported prototype dredged volumes for the fifth year are incorrect.

3. Discussion.

The deviations of the Galveston Harbor entrance model predictions from the prototype behavior are believed to be due to the cumulative effects of the following factors:

(a) Scale effects introduced by nonsimilarity of the physical processes.

(b) Insufficient information on historical and existing prototype conditions to allow adequate reproduction of the independent variables (waves, tides, and currents) in the model study.

(c) Oversimplification of the input to the model; for example, use of regular waves in the model to represent prototype wave spectra.

(d) Experimental errors.

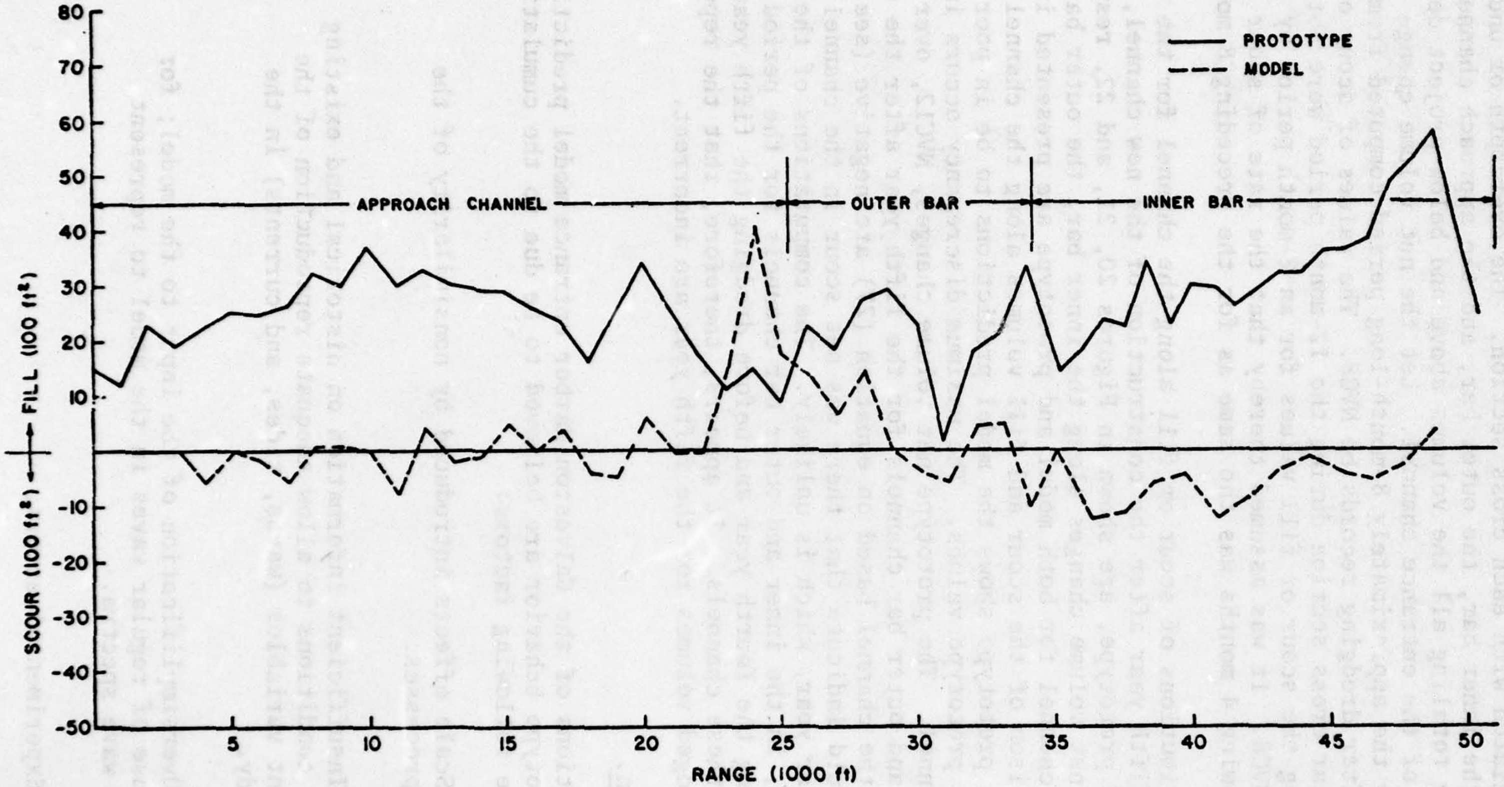

Figure 20. Comparison of model and prototype scour and fill volumes along the channel of Galveston Harbor entrance, the third year after construction.

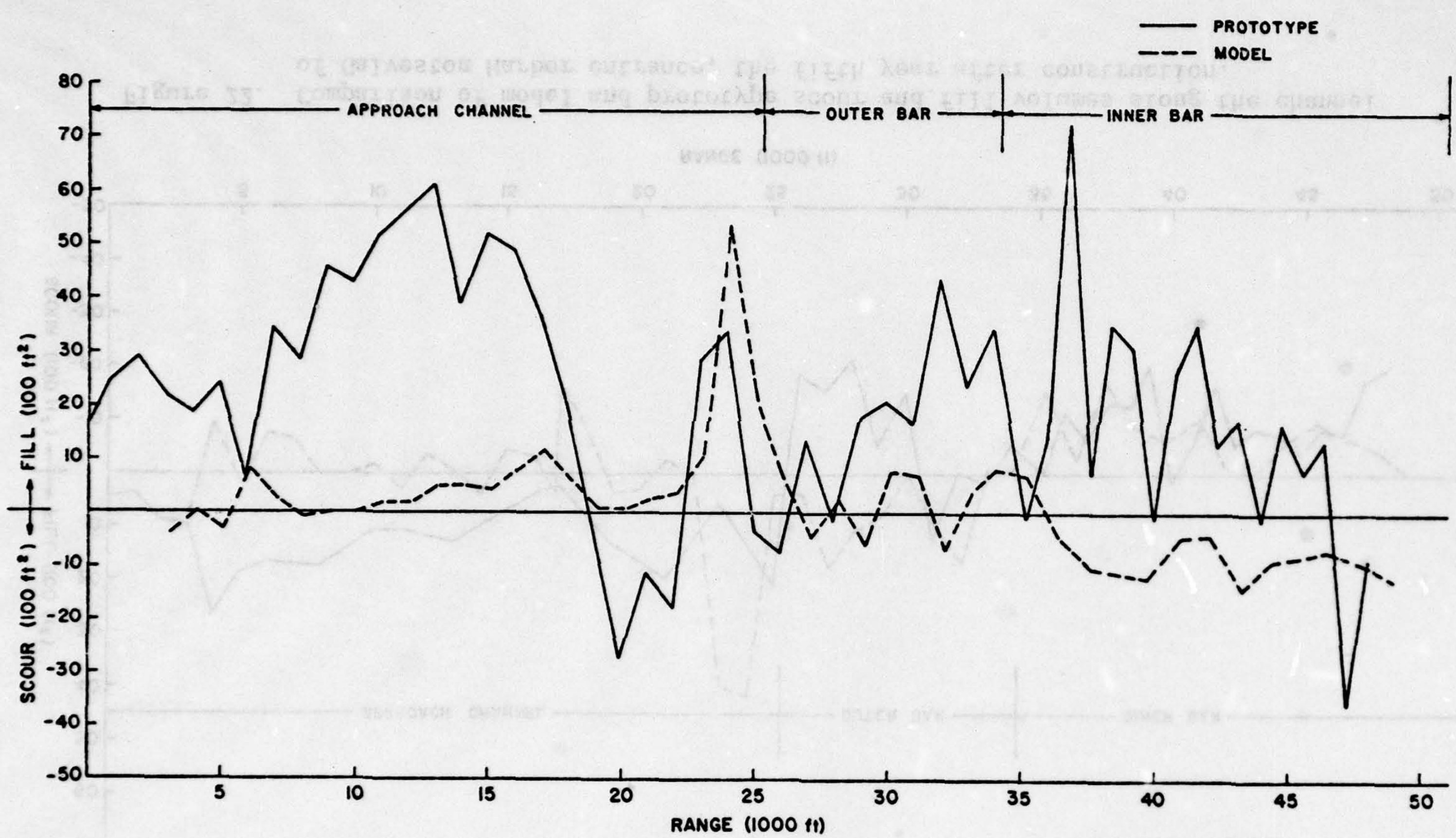

Figure 21. Comparison of model and prototype scour and fill volumes along the channel of Galveston Harbor entrance, the fourth year after construction.

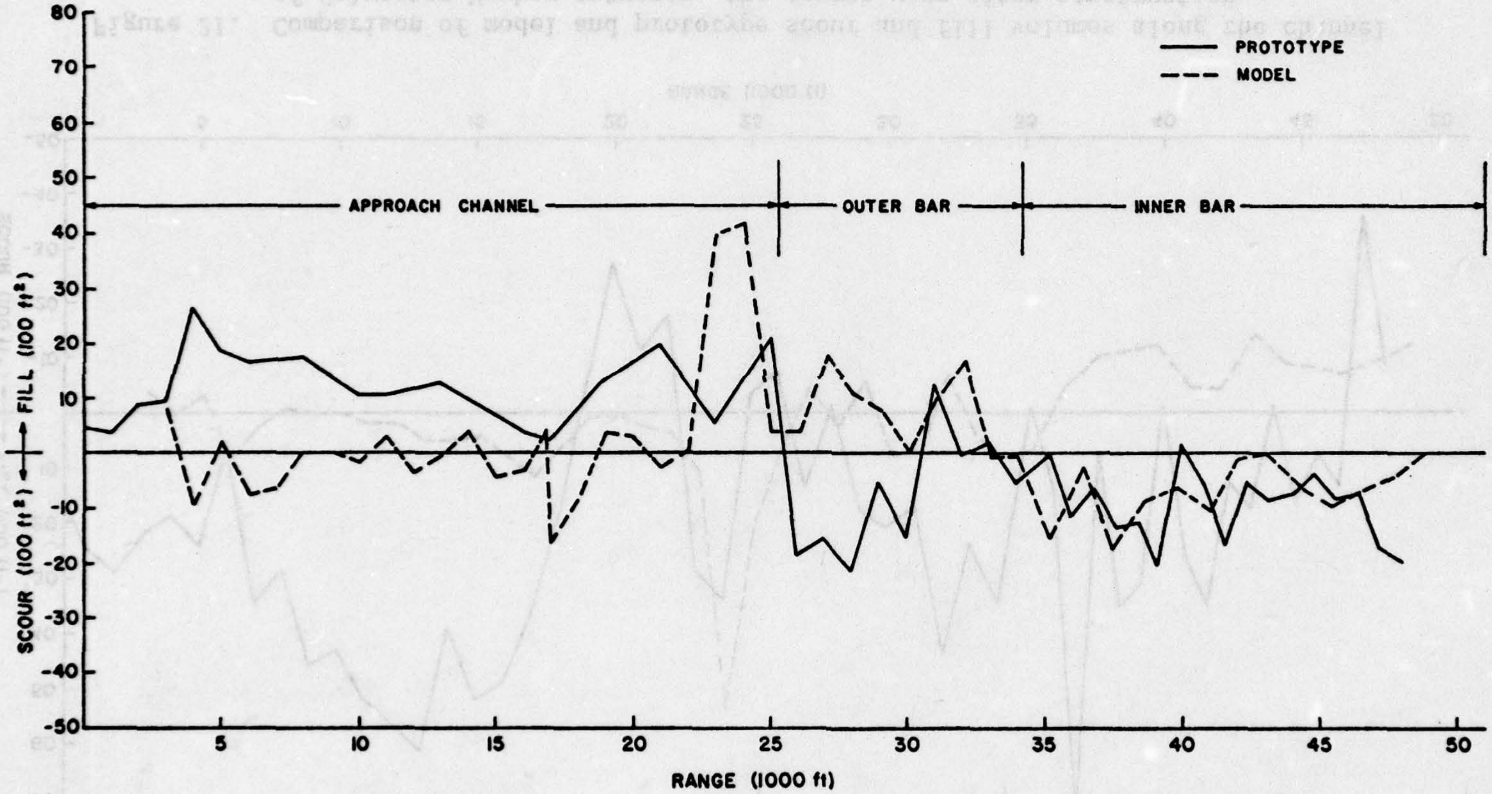

Figure 22. Comparison of model and prototype scour and fill volumes along the channel of Galveston Harbor entrance, the fifth year after construction.

Table 13. Model and prototype net hydrographic change in the navigation channel of the Galveston Harbor entrance.

Year after completion of channel	Prototype (1,000 yd³) Inner bar channel	Outer bar channel	Approach channel	Model (1,000 yd³) Inner bar channel	Outer bar channel	Approach channel
3	1,594	736	1,523	-277[1]	274	325
4	733	620	2,125	-377	336	814
5	-455	-217	1,182	-378	351	659
Total	1,872	1,139	4,830	1,032	961	1,798
Avg hydrographic change	624	380	1,610	-344	320	599

[1] Indicates scour.

In a model where the error is due to several of these factors, it is impossible to isolate the contribution of each.

a. Scale Effects. Proposed scaling laws for movable-bed coastal models are presented in Section II, where it is recommended that the model distortion be selected to produce beach profiles in the model that are similar to those in the prototype. No information on the prototype beach profiles for the model calibration period was available for the Galveston Harbor entrance model. Yalin (1971) proposed that the model distortion, α, should be

$$\lambda_Y^{-0.43} < \alpha < \lambda_Y^{-0.6} \tag{28}$$

For the Galveston Harbor entrance model, $\lambda_Y = 1{:}100$ and the value of the model distortion is 5. According to equation (28), the value of α should have been between 7.2 and 15.9.

The scaling criteria for the model-bed material and the current velocity, as discussed in Section II, are the equality of the grain parameter, G, and the particle Froude number, F_*. The ratios of the values of these parameters in the model to those in the prototype are termed scale factors. Thus, the scale factors for G and F_* are

$$\lambda_G = \lambda'_\gamma \lambda_d^3 \tag{29}$$

and

$$\lambda_{F_*} = \lambda_{V_*} \lambda_d^{-1/2} = \frac{\lambda_V \lambda_d^{1/2}}{\lambda_C} . \tag{30}$$

Assuming $\lambda_C = \sqrt{\lambda_X/\lambda_Y}$ (Bijker, 1965 suggested $\lambda_C = 0.5$) and that the model current velocity is 35 percent higher (see Sec. III, 5, d) than that based on Froude similarity, the values of the scale factor for this model are

$$\lambda_G = 242 \text{ and } \lambda_{F_*} = 0.095$$

The value of λ_G is much larger than unity indicating the model-bed material was too large or too heavy. Therefore, sediment motion could not have been expected to be initiated at the appropriate locations, nor could the pattern of scouring and shoaling have been expected to be reproduced. The value of particle Froude number scale factor, λ_{F_*}, is much smaller than unity; hence, the rate and pattern of sediment transport were not scaled correctly. These scale factors are quite significant, and it is not surprising that the model results are not in agreement with the prototype observations.

b. Insufficient Prototype Data. The prototype data available for model calibration were grossly inadequate. Two hydrographic surveys conducted 10 years apart were used for model calibration, and there were no data available on the wave climate during this period. The dredging records for the period were incomplete. Any model calibrated on the basis of such inadequate prototype data is almost certain to be unreliable. Accurate and adequate data are essential to proper model calibration, verification, and operation.

c. Oversimplification of the Prototype Data. In the calibration runs, as well as in later tests, regular monochromatic waves from a fixed direction were used in the model, though it was known that a number of major storms occurred during the 10-year period used for model calibration. Accelerated tests were used to increase the rate of movement of model-bed material. In order for reliable model predictions to be achieved, it is essential that the proper succession of storms and calm periods be reproduced in the model. Accordingly, it is concluded that the waves used in the Galveston Harbor entrance model were such a poor reproduction of the prototype wave climate that the model could not have been expected to produce reliable predictions of prototype behavior.

d. Experimental Errors. Experimental errors are unavoidable in the operation of any model. Included in these are deviations of the initial bed topography from the correct configuration; inexact reproduction of the waves or wave spectra; errors that arise in sounding the model due to compaction of the bed beneath the shoe of the sounding rod; variations in water temperature, which can affect the sediment transport rate; and errors which arise in flow metering, modeling of tides, etc. These have a cumulative effect which may or may not be significant. In the Galveston Harbor entrance model, it is believed that these experimental errors had an impact which was insignificant compared to those introduced by the incorrect modeling of the wave climate and sediment properties.

VI. SUMMARY AND CONCLUSIONS

1. Summary.

The principal objective of this investigation was to evaluate the effectiveness of movable-bed tidal inlet hydraulic models in predicting prototype behavior, by comparing the results of model studies conducted

in the United States with the corresponding data from the prototypes. A literature review was also made to determine the present understanding of and practice concerning the similitude requirements for movable-bed coastal models. The following similitude conditions are recommended for these models.

The waves should be scaled according to the Froude law, with the scale for wavelength and wave height equal to the vertical geometric scale, as given by equations (14) and (15). The use of a wave machine capable of producing irregular waves is recommended so that yearly storms can be simulated in the model. The model-bed material should have a specific gravity and diameter that satisfy equation (16), and the current velocity should be scaled according to equation (17). The permissible model distortion should be determined from the results of two-dimensional wave tank experiments performed to determine equilibrium beach profiles.

Movable-bed tidal inlet hydraulic model studies have been conducted in the United States and Canada only by WES, Vicksburg, Mississippi. WES has conducted seven such model studies. Each study was conducted on an *ad hoc* basis, in that no general similitude requirements were satisfied. The waves and currents required to reproduce prototype-bed topography changes (to some subjective degree) were arrived at by a trial procedure. Two prototype hydrographic surveys conducted some time apart and the available dredging records for the intervening period were used for model calibration. None of the model calibrations was verified because sufficient prototype data were not available. In most cases regular waves from one or more fixed direction were used in the model. A model distortion of five was adopted in all of the WES studies. Sands with mean diameters ranging from 0.18 to 0.25 millimeter were used as bed material in all models except that of the Galveston Harbor entrance, in which coal with a median diameter of 1.4 millimeters was utilized. Scour and fill maps for prototype and model were prepared and compared to ascertain if the model was satisfactorily calibrated. In addition, dredging volumes in the navigation channel were used for model calibration in two model studies. The Galveston Harbor entrance was the only tidal inlet in which the modification design developed and investigated in the model study was adopted and constructed in the prototype, and extensive prototype data were taken during the postconstruction period. The predictions from this model study were compared with observations made in the prototype. The conformity was not satisfactory.

To have a quantitative measure of the accuracy of model calibration, some quantitative indicators, such as the correlation coefficients defined in equations (20), (22), and (24), and the rms error defined by equation (25), were computed for five of the WES model studies. For the Absecon Inlet model, the contours of difference between model and prototype changes in the bed configuration were also plotted. The model and prototype shoaling rates and distributions in the navigation channel of the Galveston Harbor entrance were computed from the available model and prototype hydrographic soundings within the navigation channel for the postconstruction period.

In general, the calibration of the models was judged unsatisfactory in terms of bed change reproduction if model and prototype sounding errors are considered negligible. Larger sounding error estimates result in better apparent agreement between model and prototype, but tend to prevent effective use of the statistical measures since their use obscures much of the measured bed changes. In some cases the correlation coefficients are negative, which means that the model was predicting scour at some, if not most, locations where fill occurred in the prototype, and vice versa. The shoaling rates and spatial distributions in the navigation channel of the Galveston Harbor entrance predicted by the model for the postconstruction period are also not in agreement with the prototype observations.

2. Evaluation.

The calibration deficiencies observed in all of the WES models investigated in this study, and the differences between prototype behavior and model prediction for the Galveston Harbor entrance model are believed to be due to the cumulative effects of the following factors: (a) scale effects introduced by nonsimilarity between model and prototype of the physical processes; (b) insufficient information on historical and existing prototype conditions to allow adequate calibration and operation of the model; (c) oversimplification of the prototype data, especially that on wave climate, for reproduction in the model; and (d) experimental errors. It is almost impossible to determine the contribution of each of these factors to the resulting errors in the model predictions. However, certain observations were made. The prototype data utilized for model calibration were inadequate in all of these WES model studies. Only two hydrographic surveys, generally incomplete ones, were available for calibration. In one case (Galveston Harbor entrance) the period between the two hydrographic surveys was 10 years, which is much too long, while in another case (Masonboro Inlet) it was only 9 months (which is not even one complete annual cycle) and is thus too short. Practically no data were available on wave climate. In some cases even the prototype-bed material mean diameter was not available. It cannot be overemphasized that accurate and adequate prototype data covering a minimum of 1 year, and preferably 2 or more, are absolutely essential for achieving acceptable model performance. In some instances when satisfactory bed topography could not be reproduced, even after numerous trial tests, arbitrary adjustments in the model waves, tides, or currents were made to continue the model testing. A model distortion of five was arbitrarily selected for each model study. Too much time and effort was occupied by determining the waves and currents in the model for satisfactory reproduction of the bed configuration. It is believed that the time required for calibration can be reduced if certain similitude requirements are satisfied in the model. Although it was not possible to resolve whether the reproduction of irregular waves is essential for satisfactory model performance, it is clear that better input data used in the model will lead to better results. Moreover, since a large percentage of sediment transport takes place during high waves, which occur during only a small fraction of time, while the

average or low waves which prevail a large percent of the time carry a small percentage of the sediment, it is desirable to reproduce the wave climate (including storms) in the model. Furthermore, if the proper succession of storms and calm periods is an essential condition for the dynamic equilibrium of a coast, then the practice of using accelerated tests adopted by WES in some of the model studies is unacceptable.

3. Recommendations for Further Studies.

a. Additional evaluative movable-bed model studies similar to the Masonboro Inlet model study should be conducted for other inlets. There should be enough prototype data available for both the preconstruction condition to calibrate and verify the model, and for the postconstruction period to evaluate the capabilities and limitations of the model.

b. To evaluate the importance of the similitude conditions, a test model should be calibrated separately by employing the trial-and-error procedure currently followed by WES, and by satisfying the similitude requirements recommended here.

c. A test model should be calibrated using regular waves of both constant and varying heights, periods, and directions (irregular waves), to resolve the question of whether the proper succession of storms and calm periods is essential for a proper model performance.

d. It appears that certain European laboratories have made significant advances in the art and science of movable-bed modeling. Most of the European laboratories use lightweight material for the model-bed sediment and irregular waves in the model. The European practice followed in conduct of model studies of the type discussed here should be reviewed and evaluated.

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APPENDIX A

ORGANIZATIONS IN THE UNITED STATES AND CANADA ENGAGED IN COASTAL MODEL STUDIES

United States

Officer in Charge
Hydraulic Laboratory
Lehigh University
Bethlehem, Pennsylvania 18015

Newport Laboratory
Naval Underwater System Center
Newport, Rhode Island 02840

Officer in Charge
Hydraulic Engineering Laboratory
Department of Civil Engineering
University of Texas
Austin, Texas 78712

Head of Coastal and Ocean Engineering Division
Department of Civil Engineering
Hydromechanics Laboratory
Texas A&M University
College Station, Texas 77843

Director
Charles W. Harris Hydraulics Laboratory
Department of Civil Engineering
University of Washington
Seattle, Washington 78105

Chairman
Department of Oceanography
University of Washington
Seattle, Washington 78105

Tetra Tech, Inc.
630 N. Rosemead Boulevard
Pasadena, California 91107

U.S. Army Engineer District, Galveston
P.O. Box 1229
Galveston, Texas 77550

U.S. Army Engineer Waterways Experiment Station
P.O. Box 631
Vicksburg, Mississippi 39180

U.S. Army, Corps of Engineers
Coastal Engineering Research Center
Kingman Building
Fort Belvoir, Virginia 22060

Canada

Professor T. Blench
Hydraulics Laboratory
Department of Civil Engineering
University of Alberta
Edmonton 61, Alberta

Head, Department of Civil Engineering
Kingston Hydraulic Laboratories
Queens University at Kingston
Ontario

President
LaSalle Hydraulic Laboratory Ltd.
0250 St. Patrick
LaSalle, P.Q.

Vice President of Engineering Laboratory
H.G. Acres Limited
1259 Dorchester Road
Niagara Falls, Ontario

President
Western Canada Hydraulic Laboratories Ltd.
1186 Pipeline Road
Port Coquitlam
British Columbia

Head, Hydraulic Division
Hydrodynamic Laboratory
Ecole Polytechnique
2500 Marie-Guyard Avenue
Montreal 250, Quebec

Head of Civil Engineering
University of Ottawa
Ottawa, Ontario KIN 6N5

Canada Department of Public Works
1110 W. Georgia Street
Vancouver, British Columbia

APPENDIX B

WATERWAYS EXPERIMENT STATION COMMENTS ON THE REPORT "AN EVALUATION OF MOVABLE-BED TIDAL INLET MODELS"

by

H.B. Simmons, W.H. McAnally, Jr., and C.L. Vincent

1. The purposes of this appendix are: (a) to assure that a clear understanding exists of the purpose of this report; (b) to assure that a clear understanding exists of the purposes of the inlet studies discussed in the report; and (c) to provide comments on the contents of the report.

2. The purpose of this report is to assess the reliability of movable-bed tidal inlet hydraulic models as predictors of prototype behavior. It should be clearly understood that the object of the study was not to evaluate the effectiveness of the inlet studies in meeting their study objectives.

3. Since the report quite logically focuses on the one inlet study that developed an improvement plan which was essentially constructed in the prototype, i.e., Galveston Harbor entrance,* the objectives of the Galveston Harbor entrance study are explored further.

4. In 1960 when the Galveston District contacted the U.S. Army Engineer Waterways Experiment Station (WES) concerning the problem area, the primary concern was the alinement of the navigation channel. The then existing navigation channel was quite difficult to navigate and undermining of the north jetty by strong tidal currents posed a distinct threat. As a result, the Galveston District requested that WES address these two problems with the additional request that, within reasonable funding expenditures, the best possible estimate of shoaling to be expected in a satisfactorily realined entrance channel also be provided. The study was conducted and the primary objectives of the study were successfully met. Presently, a much-improved navigation channel exists through Galveston entrance, and the north jetty no longer is subject to the threat of undermining. Because the primary problems of concern to the Galveston District were successfully resolved, WES considers that the model study was an outstanding success.

5. At the time the decision was made by Galveston District to implement the study recommendations, WES recognized that, for the first time, an opportunity to obtain prototype confirmation existed. At the request of WES, the Galveston District expanded the planned surveys to a series of fairly comprehensive surveys of the entrance area. These

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*H.B. Simmons and R.A. Boland, Jr., "Model Study of Galveston Harbor Entrance, Texas; Hydraulic Model Investigation," Technical Report H-69-2, Feb. 1969, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

expanded surveys were for the specific purpose of providing information on the effectiveness of the model study in predicting the maintenance dredging requirements of the realined entrance channel.

6. In 1974, WES concluded that data for a sufficient period of time existed to allow an analysis of the model study to be conducted. This study was subsequently conducted and the results published.* Although the study included extensive evaluation of model and prototype data, the basic fact is that results from the model indicated an overall increase in shoaling of 44 percent whereas the prototype experienced a 77-percent increase.

7. It is not the intent of this appendix to discuss the two approaches taken (main text of this report and foot-noted reference); however, the two studies do involve different approaches to evaluation of the accuracy of the Galveston Harbor entrance model results. In reviewing a draft of this report, two areas of concern are identified. In the first, the report applies the criterion of high linear correlation coefficients to bed elevations in model and prototype and concludes that, for the cases studied, model verification was deficient. The following comments are presented:

a. The criterion of high correlation coefficients *has not* been shown to be necessary for similitude of other phenomena, such as navigation channel shoaling.

b. High correlation of bed elevations has not been shown to be attainable within practical limits of time and cost.

c The conclusions drawn do not consider the possibility of purposefully neglecting some aspects of similitude in order to obtain a cost-effective solution to some other phenomenon.

d. The conclusions do *not* reflect a realistic evaluation of the accuracy of bathymetric data.

8. The second general area of concern is the impractical portrayal of the requirements for similitude. The proposed requirements for model scales, distortion, and sediment characteristics may provide better model results; however, evidence to demonstrate this is not presented. As only one example, WES experience with the use of a large number of model sediments for numerous model studies conducted over the past years has led to the conclusion that a sediment that satisfies Equation 16 will not prove to be practical.

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*J.V. Letter, Jr., and W.H. McAnally, Jr., "Physical Hydraulic Models, Assessment of Predictive Capabilities; Movable-Bed Model of Galveston Harbor Entrance," Research Report H-75-3, Report 2, Nov. 1977, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

9. Many of the studies on which the authors base their similitude arguments did not appear in the literature until after the termination of most of the model studies cited. The information presented in recent literature, when applied with an understanding of the physical phenomena involved and appreciation for practical modeling methods, may well improve future modeling efforts.

10. Another facet of unrealistic similitude requirements is the assumption of prototype data availability, reliability, and accuracy. The report recommends use of "irregular" waves in models but does not suggest how these waves are to be defined. At many coastal locations, even crude wave climate estimates are lacking and virtually nowhere are wave conditions during storms defined. Even if one were to have an accurate and reliable wave data base, he would still face a major unresolved research problem in deciding how to model the wave climate such that the sediment transport would be reproduced properly. The similitude questions, relative to sediment transport, which can arise in using a wave spectrum and, even more importantly, in considering nearshore circulation (edge waves, wave setup, wave groups, shelf oscillation, etc.) are of such a research magnitude that the report recommendation to use irregular waves in such models is unrealistic.

11. There is considerable difference between modeling a time sequence of wave conditions (such as varying a monochromatic height and period in a time sequence) and in reproducing a wave spectrum where at any time the water-surface elevation is presumably a sum of a number of simultaneous wave trains. The report implies modeling an exact wave spectrum. This is not possible because a wave spectrum is a statistical estimate of a statistical representation of the water-surface movement. It is even further inappropriate when it is realized that there are an infinite number of wave height-period sequences which can produce a given wave spectrum (to the degree of precision that it can be estimated in the field). It is further not clear that if two or three such sequences were input to the model, the resulting effects would be the same. One cannot presume that at any point in a storm the wave motion is suitably represented by some simple height, period, and direction because it is typically during a storm that both the spectral widths and directional spread tend to be widest. If representation of a storm in the model requires a spectrum, then it is evident that it must be two-dimensional. We know of no generating mechanism other than an air pressure mechanism to do this, and these devices do not produce reproducible results. Finally, if by irregular waves, the authors do imply a train of regular waves at different heights and periods, great care must be taken. If there is too rapid a variation in these characteristics, the water-surface motion will tend to be a spectrum of waves. If this is the case, then it is possible that the spectrum so generated may be transformed by nonlinear interactions among the different waves. It is not obvious that in a distorted-scale model the evolution of these interactions are in similitude with those in the prototype because the time rate of change for action density for a wave number in a spectrum is a nonlinear function of action densities and a coupling coefficient

which depends upon wave number. In addition, generation of a train of waves of varying height and period is not equivalent to the best pattern resulting from the interaction of two wave trains of varying period. This problem requires substantial research.

12. We concur in the recommendation that a more rigorous attempt to reproduce a representative variety of wave heights, directions, and periods be made in future studies, but to make such a recommendation casually and to fault older model studies for inadequate wave modeling implies that the state of the art and understanding of both coastal processes and modeling at the time of those studies were such that the studies were improper. This is not the case.

13. The concept of including a data error margin in the correlation computations is a good one, but the report ignores its own error analysis when it states that verification of the models was deficient. Bathymetric data in coastal waters are subject to substantial systematic and random errors, and older data are not sufficiently accurate to use in a correlation analysis unless depth changes are rather large. The report does not present detailed results to demonstrate validity of the analysis under these conditions.

14. In conclusion, WES fully endorses the objective of assessing the reliability of movable-bed models of tidal inlets. The report has many good points; however, care should be taken in evaluating the effectiveness of model results from the standpoint of both evaluating the accuracy of the predictions and meeting the objective of specific studies.

Jain, Subhash C.

An evaluation of movable-bed tidal inlet models / by S.C. Jain and J.F. Kennedy. – Ft. Belvoir, Va. : U.S. Coastal Engineering Research Center ; Springfield, Va. : available from National Technical Information Service, 1979.

82 p. : ill. (GITI report ; 17) (Contract – U.S. Coastal Engineering Research Center ; DACW72-76-C-0003)

"Prepared by Iowa Institute of Hydraulic Research, University of Iowa."

"General Investigation of Tidal Inlets – a program of research conducted jointly by U.S. Army Coastal Engineering Research Center, Fort Belvoir, Virginia, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Mississippi."

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The objective of this study was to evaluate the effectiveness of movable-bed tidal inlet hydraulic models in predicting prototype behavior, by comparing model predictions with the observations made in the prototype, and to examine the scaling requirements for such models.

1. Movable beds. 2. Tidal models. 3. Tidal hydraulics. 4. Tidal inlets. I. Title. II. Kennedy, John F., joint author. III. Series: U.S. Army, Corps of Egineers. GITI report ; 17. IV. Series: U.S. Coastal Engineering Research Center. Contract ; DACW72-76-C-0003.

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